8-2007

Marquette Interchange Phase I Final Report

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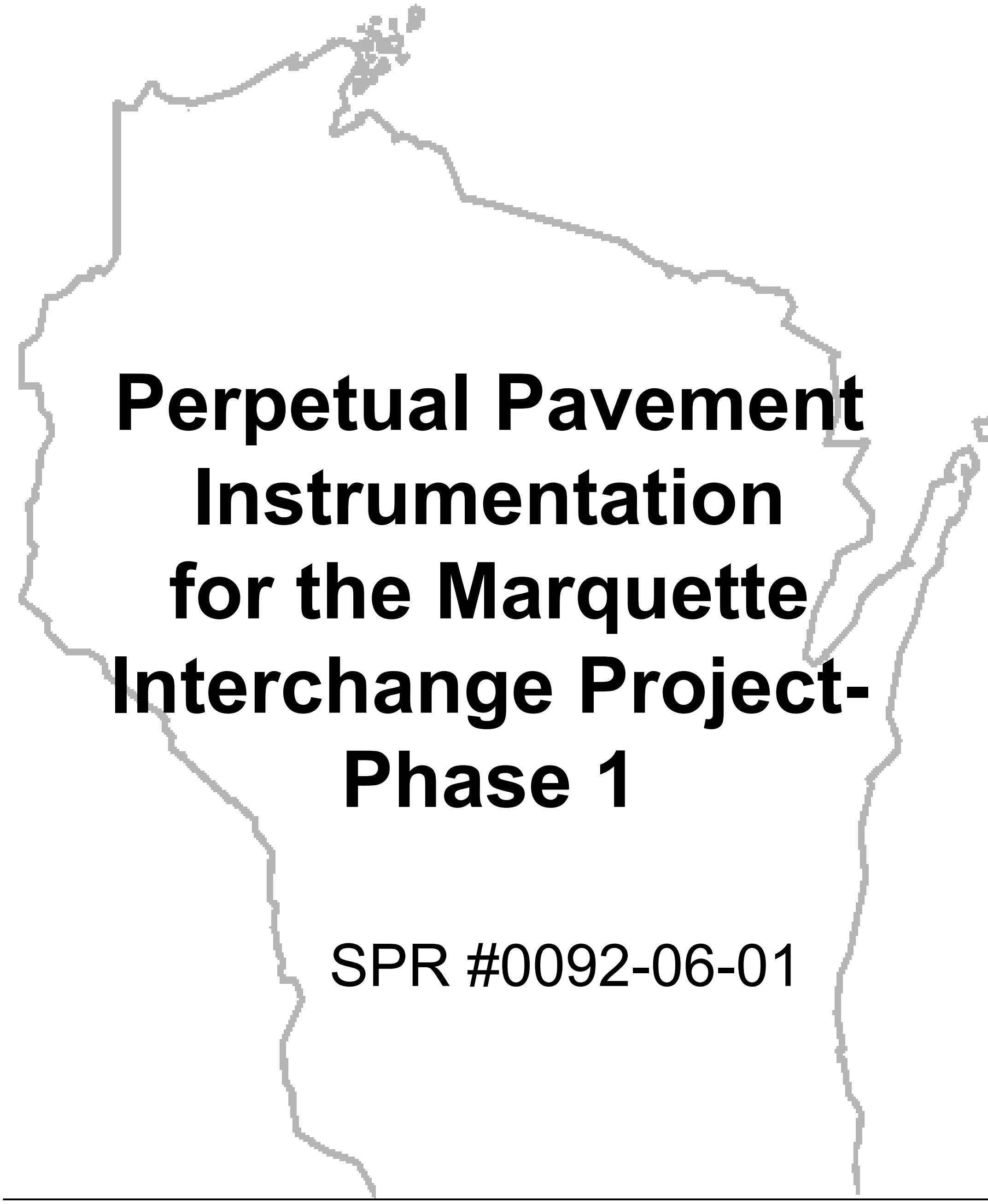

Perpetual Pavement Instrumentation for the Marquette Interchange Project-Phase 1

SPR #0092-06-01

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August 2007

WHRP 07-11

Marquette Interchange Perpetual Pavement Instrumentation Project: Phase I Final Report

Presented To:

Wisconsin Highway Research Program

Submitted By:

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August 15, 2007

Technical Report Documentation Page

1. Report No.	2. Government Accession No	3. Recipient's Catalog No
WHRP 07-11		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
Perpetual Pavement Instrumentation for the Marquette Interchange Project – Phase 1 Final Report	5. Report Date: September 2007 6. Performing Organization Code: Univ. of Wisconsin - Madison
7. Authors	**8. Performing Organization Report No.**
Nicholas J. Hornyak, James A. Crovetti, David E. Newman, Jay P. Schabelski	
9. Performing Organization Name and Address	**10. Work Unit No. (TRAIS)**
Transportation Research Center Marquette University	11. Contract or Grant No. WisDOT SPR# 0092-06-01
12. Sponsoring Agency Name and Address	**13. Type of Report and Period Covered**
Wisconsin Department of Transportation Division of Business Services Research Coordination Section 4802 Sheboygan Ave. Rm 104 Madison, WI 53707	Final Report, 2005-2007 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report provides details on the design, installation and monitoring of a pavement instrumentation system for the analysis of load-induced stresses and strains within a perpetual HMA pavement system. The HMA pavement was constructed as part of an urban highway improvement project in the City of Milwaukee, Wisconsin. The outer wheel path of the outside lane was instrumented with asphalt strain sensors, base and subgrade pressure sensors, subgrade moisture and temperature sensors, HMA layer temperature sensors, traffic wander strips and a weigh in motion system. Environmental sensors for air temperature, wind speed and solar radiation are also included. The system captures the pavement response from each axle loading and transmits the data through a wireless link to a resident database at Marquette University. The collected data will be used to estimate the fatigue life of the perpetual HMA pavement and to modify, as necessary, pavement design procedures used within the State of Wisconsin.

17. Key Words	18. Distribution Statement
Perpetual pavement, asphalt strain, fatigue analysis, traffic wander pattern, weigh in motion, environmental sensors.	No restriction. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield VA 22161

19. Security Classif.(of this report)	19. Security Classif. (of this page)	20. No. of Pages	21. Price
Unclassified	Unclassified		

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

Disclaimer

This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project # 0092-06-01. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

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Acknowledgements

The authors wish to thank the Wisconsin DOT and North-Leg project contractors for their valuable cooperation during this research study. A special thanks goes to the following people for their assistance during the study:

Wisconsin DOT
Len Makowski
Deb Schwerman
Judy Ryan
Frank Rivera

Walsh Construction
Nick Faul

Outdoor Lighting
Gary Dlugopolski
Tony Nedoma

TAPCO
Brian Scharles
Bob Lingnofski

Payne & Dolan
Signe Richelt
Todd Hughes
Bill Evenich

Collins Engineers
Frank Hines
Tom Collins

HNTB
Paul Kutz

Executive Summary

Project Summary

The first phase of this project was focused on developing and implementing an instrumentation plan for a section of a hot mix asphalt (HMA) perpetual pavement located within the north leg of the Marquette Interchange project. The main objectives of this project as a whole are to instrument a pavement to acquire the necessary data to provide information necessary for a comprehensive mechanistic-empirical pavement appraisal. The information generated from this project will help calibrate certain design factors to account for local conditions.

Background

Pavement design practices have relied on concepts generated years ago in tests conducted by AASHTO and other agencies. These design practices are currently being transitioned from the largely empirical based design methods to those that are based heavily on mechanics of materials with some empirical elements still residing within. This transition in design practices requires careful consideration of the variables which are sensitive to location, traffic patterns, and environment of the regional area.

In April 2005 a proposal to instrument a HMA perpetual pavement was submitted to the Wisconsin Highway Research Program and subsequently awarded to the Transportation Research Center at Marquette University.

Process

This specific phase of the project was carried out in multiple tasks. A detailed implementation plan was generated to supplement the general plan laid out in the original proposal. Within this detailed plan, specific brands and models of sensors were selected based upon detailed literature reviews, direct communication with members of the engineering community, and also through some experimental procedures. This process helped to develop a list of the equipment that was best suited for the job and budget. Alternative equipment plans were also developed to suit any changes in design of the Marquette Interchange project that may have occurred over the duration before installation. The proposed sensor list included asphalt strain gauges, earth pressure cells, moisture probes, temperature sensors, a wheel wander grid, a weigh-in-motion system, various environmental sensors, and data collection/transmission/storage devices.

Another important aspect the project was the proposed location of the test section. The test section needed to provide clear traffic flow with little weaving and other interruptions while still acting as a representative segment of pavement. The location also needed to provide for other needs such as electrical power and accessibility.

Once the detailed implementation plan was generated and approved, the installation procedures needed to integrated into the scheduling requirements of the other construction activities on the north leg project. This required communicating with the various construction contractors to make those involved on the construction project aware of activities of this research project. The project was closely monitored and frequently visited so the installation of the equipment could go as planned without disrupting the activities of the other construction crews. Additionally it was important to monitor construction crews and inform them as needed to protect the sensitive equipment from damage.

The physical installation of the sensors in the pavement structure was a very critical step in the whole project. The dynamic pavement sensors (asphalt strain gauges, earth pressure cells, etc.) are the main focus of the research, and a large number of sensors not surviving the installation could have compromised the entire project. Engineering ingenuity and careful practices, taking note to follow manufacturers' warnings and recommendations when available, were used to ensure a good sensor survival rate.

A great deal of time was also spent setting up the equipment used to read the numerous sensors. This included careful calibration of many sensors used in the project and also the software needed to read, monitor, and manage the system.

Findings

Because of the careful planning and cooperation with the contractors the installation of the pavement sensors was a success. Immediately after paving, only one strain sensor was not responding completely while another was producing an excessively noisy signal, but still operational. All other strain gauges and earth pressure cells were operational. Up to the time of the publication of this report, data collection is underway of the traffic data and being stored on the project database. The second phase of this project, which is in progress, will provide the necessary means of data distribution and data analysis.

Recommendations

While no explicit recommendations regarding expected perpetual pavement performance are yet available, this research is expected to provide the engineering community with a wealth of high quality data that is the most complete and thorough set known to exist at this time. Implicit recommendations can found throughout this report from the proper selection of sensors, test section location, and overall guidelines for the implementation of other such projects that may be similar in part, or in whole, to this project. It is hoped that this report can make itself useful for others doing similar work in the future.

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Chapter 1 - Literature Review

This report has been submitted for fulfillment of task 5 in the original research proposal submitted to the Wisconsin Highway Research Program for the Marquette Interchange Instrumentation Project. The report covers all of the work done for this project covering preliminary literature review, field instrumentation plan, the procedures for installation of the individual instruments and system components, and finally the system demonstration.

In fulfillment of Task 1 in the original proposal, a literature review of past research in this particular area of study was conducted to help mold the instrumentation and data acquisition plan. Review of past literature gave insight to what ideas have worked and provided the most valuable information. The research may have been limited due to the current technology at the time or unforeseen troubles. Tailoring this research to the past also makes the new research somewhat comparable to the past. The two main research projects/programs that have been under scrutiny are the MnROAD study and NCAT test track.

1.1 MnROAD Study(1 - 8)

The MnROAD program was sponsored by the Minnesota Department of Transportation and carried out by researchers at the University of Minnesota. The program involved studying both a test track for controlled loading and also a portion of Interstate 94 for loading under real conditions. The focus of the project was very broad and covered many aspects of pavement and highway design. Of interest to this research was the work done towards understanding the structural response of different flexible pavements. Some outcomes of the project included calibrating pavement models to the local conditions in the region thus improving the accuracy of their pavement design procedures. The work done also helped to shape a mechanistic-empirical design process.

To measure the structural response of both PCC and HMA pavements, over 4,500 sensors were installed into the pavement structures. Of these 1,151 of them were used to dynamically measure pavement response. Amongst the numerous sensors were asphalt strain gauges and earth pressure cells. These two sensor types were the main resource for acquiring the dynamic load response of the pavements. Many of the other sensors used were focused primarily for acquiring information regarding the environmental conditions and conditions for the supporting layers below the asphalt.

The strain sensors were arranged in groups of three spanning across a wheel-path. Some were placed to measure strain transversely to traffic while others were placed to measure longitudinally (in the direction of traffic), although no implications were given which orientation was used and why. Previous pilot studies had been carried out but mainly focused on the type of instruments to utilize and not necessarily with the location and arrangement patterns.

Optim Electronics MEGADAC data acquisition systems were used to collect the data coming from the instruments. Acquisition was done at set time intervals and not necessarily taken continuously.

Researchers did note during the project that numerous sensors eventually failed, crippling the effort. They also reported that they needed more data consisting of more axle configurations to use in creating and calibrating models. Work is ongoing at the MnROAD project site, but research regarding structural response has subsided.

1.2 NCAT*(9 - 17)*

The National Center for Asphalt Technology (NCAT) at Auburn University test track was started in 2000 and has continued today to be a source of excellent research concerning asphalt technology. The track consists of forty-five flexible pavement test sections, each 200 feet long, and is constantly being loaded by controlled semi-trucks. The trucks have been purchased for the sole purpose of applying load repetitions to the pavement and are driven on for eighteen hours a day, making the test track an accelerated performance testing facility (consuming 10 to 15 years of design life in 2 years). Within the numerous test sections are a huge variety of different research activities.

In 2004 eight sections of the NCAT test track were devoted to installing sensors for measuring dynamic pavement responses. The eight sections selected were constructed of asphalt with varying structures and asphalt mix designs. Many CTL brand asphalt strain gauges were installed as the primary source of data for pavement analysis. Along with these a handful of earth pressure cells (of two different types), vertical compression gauges, soil moisture

(TDR) probes, and temperature probes were installed to provide supplemental, but important data.

The installation of the sensors was a success with only a few gauges not surviving installation. Low speed data was recorded for the environmental sensors such as temperature and soil moisture. The strain sensors and earth pressure cells were recorded at high speed under trafficking from the calibrated test vehicles. The data was analyzed in a piecewise manner; taking the information that was considered most crucial.

The information taken from the study was used to calibrate the pavement design processes to the local variables. The stated objectives of this particular research were to validate mechanistic pavement models, develop transfer functions for typical asphalt mixtures and pavement cross-sections, study the dynamic effects on pavement deterioration, and to evaluate the effect of layer thickness and polymer modification on structural performance.

Chapter 2 - Field Instrumentation Plan

2.1 Problem Statement

This pavement instrumentation plan was developed to provide pavement response data necessary for a detailed assessment of stress and strain induced by traffic and environmental loadings and to provide information needed to validate fatigue models used for the design of long-life pavement systems. During the Spring/Summer of 2006, HMA perpetual pavements will be placed along the North Leg of the Marquette Interchange reconstruction project. This project offers a significant opportunity to examine the in-service performance of a high profile, highly-trafficked HMA perpetual pavement and has the potential to provide benchmark performance data that can be used to validate pavement design models and help ensure the most cost-effective usage of pavement materials.

The Marquette University Transportation Research Center (MU-TRC) research team has reviewed numerous published research reports and manufacturers literature relevant to the design, installation, operation, maintenance and costs of pavement sensors and data collection/transmission equipment. Research reports from the MnROAD study (1 - 8), the Virginia SmartRoad (18) and the NCAT test track (9 - 17) provided significant contributions to this study. Additional research papers presented at the Transportation Research Board and personal communications with various authors also provided significant input to this process. Construction plans for the North Leg pavements have been reviewed to identify opportunities/constraints for integrating pavement sensors and related recordation equipment into the defined project limits. The results of these reviews have been synthesized into this plan for the instrumentation package that best satisfies project goals.

2.2 Instrumentation Location

The project plans for the North Leg pavements were reviewed in detail to identify potential instrumentation locations. A number of meetings with the Marquette Interchange construction team were also held to discuss the various instrumentation scenarios. A paramount concern for locating the instrumentation was to identify a project location with minimal ramp conflicts or other pavement design details which might result in significant traffic wandering within the instrumented lane. The selected location also needs to be in the vicinity of pull boxes located along the project length to ensure that conduit lines planned for installation as part of the interchange project would be available for use to provide power and data transmission lines to the instrumentation location.

A review of the project plans provided a number of possible locations, including the areas near Wisconsin Avenue, Brown Street and North Avenue. The Brown Street and North Avenue locations were identified as the two preferred locations due to their proximity to planned pull boxes and existing communication vaults. The disadvantage of the Brown Street location, between stations 404+00 and 406+00, is the presence of an auxiliary lane which serves as the North Avenue exit ramp. This exit ramp may result in substantial traffic wandering within the zone of instrumentation.

The North Avenue location, between stations 411+00 and 415+50, represents a standard 3-lane pavement section where minimal lane wandering is anticipated. This is the recommended installation location but there are some limitations which bear noting. Between stations 411+00 and 413+00 the typical proposed section includes a super elevated section with a surface cross-slope of 5.10%, reducing to approximately 0.80% by station 415+00. The preference would be locate the instrumentation package in a section without significant super elevation; however it is also desired to have an installation location which is at least 200 feet from the end of construction to minimize construction variances. Locating the sensors at station 413+50 would be preferred from this criterion; however, the current project plans include traffic monitoring loops to be installed at this location. As such, it is recommended that the installation package be located between stations 413+50 and 414+00.

The proposed pavement section within these limits transitions from a cross slope of 4.43% to 3.10%. The grass median between the mainline pavement and the North Avenue exit ramp is approximately 70 feet wide in the section with a grade changing from 7.95% to 9.30%. This available area should allow for ease in locating the necessary roadside cabinet and supporting pad without the need for protective barriers.

2.3 Asphalt Strain

The dynamic strain response at the bottom of the HMA layer under moving wheel loads is commonly associated with the fatigue performance of the HMA layers, in terms of bottom-up cracking. To capture these strains under all moving wheel loads, asphalt strain sensors will be positioned with both longitudinal and transverse orientations within the outer wheel path of the outer lane to allow for the analysis of spatial variations in strain accumulations. Asphalt strain sensors manufactured by CTL, Dynatest and Tokyo-Sakki were obtained and tested at Marquette University to better understand the behavior and linearity of these sensors.

A single CTL asphalt strain sensor, model number ASG-152, was purchased by Marquette University using internal funds. The ASG-152 is a 350 ohm, full bridge 6/6 nylon rod based sensor configured in an “H” shape. Minor workmanship problems were noted (misaligned aluminum “wings”, skewed threads), but the sensor appears to perform as advertised. The full bridge configuration of the sensor eliminates the need for costly precision completion resistors and provides a relatively large output voltage. The device is simple and there is ample evidence from other researchers to assure us that it is rugged enough for consideration provided caution is used when installing the sensor. Customer support for this product was disappointing during our initial trials. Documentation for the sensor, while present, was provided in a form that was not readily useable. Support for installation, if needed, has been assured by CTL’s sales staff.

A single Dynatest FTC II A (Past II-AC) strain sensor was obtained on loan from the University of Illinois. The Past II-AC is a 120 ohm ¼ bridge epoxy fiberglass based sensor. The Dynatest sensor appears to be well constructed, but this is based on a very superficial examination as the sensor is a coated, sealed unit. Stated modulus is ~320,000 psi, so it is assumed that the predominant material is fiberglass. The Dynatest gage is approx. 2/3 the physical size of the CTL sensor, and lacks the vertical “wing” component present in the CTL sensor. This *may* lead to a less positive “lock” in the asphalt pavement, resulting in the sensor slipping in the pavement structure, thus generating less strain for a given load. The 120 strain gage used in this sensor will generate more heat/volt excitation than a 350 ohm gage, and the ¼ bridge configuration requires the use of precision bridge completion resistors.

A single Tokyo Sokki KM-100HAS embedment sensor was obtained on loan from the manufacturer. The KM-100HAS is a 350 ohm, full bridge temperature compensated strain transducer. The sensor is designed around a tube structure with a proprietary mechanism inside that deforms in response to either a tensile or compressive load. The KM-100HAS sensor appears to be well constructed; again, by superficial examination only. The sensor appears to be a slightly modified version of a PCC embedment gage, and the physical anchorage provided by the round (#2 rebar) lateral protrusions is, at this time, questionable.

Testing conducted at Marquette University indicates all sensors produce a linear response to loading but it is not yet possible to ensure that these sensors are providing precise measurements of strain. Marquette University recently purchased a high resolution extensometer with a resolution of 10 microstrain which will be used to verify the accuracy and precision of the strain sensors and to provide data for verification/adjustment of the calibration factors provided by sensor manufacturers.

It is recommended that strain sensors from both Dynatest and CTL be incorporated into this instrumentation plan. Both sensors have a proven record of performance but to date have not been used in tandem on any research project to test the long-term survival of these sensors. It is further recommended that 16 sensors be obtained from CTL and eight sensors from Dynatest. These sensors will be configured in three replicate groups, each containing five sensors positioned in the transverse direction and three in the longitudinal direction, as shown in Figure 2-1. Transverse spacing between adjacent sensors within each group is 2 feet while longitudinal spacing between sensors is 1 ft. Each sensor group is spaced at a 7 ft midpoint spacing, resulting in a minimum spacing of 5 ft between the nearest sensor within each adjacent group. All sensors will be installed at the bottom of the HMA pavement during normal construction operations.

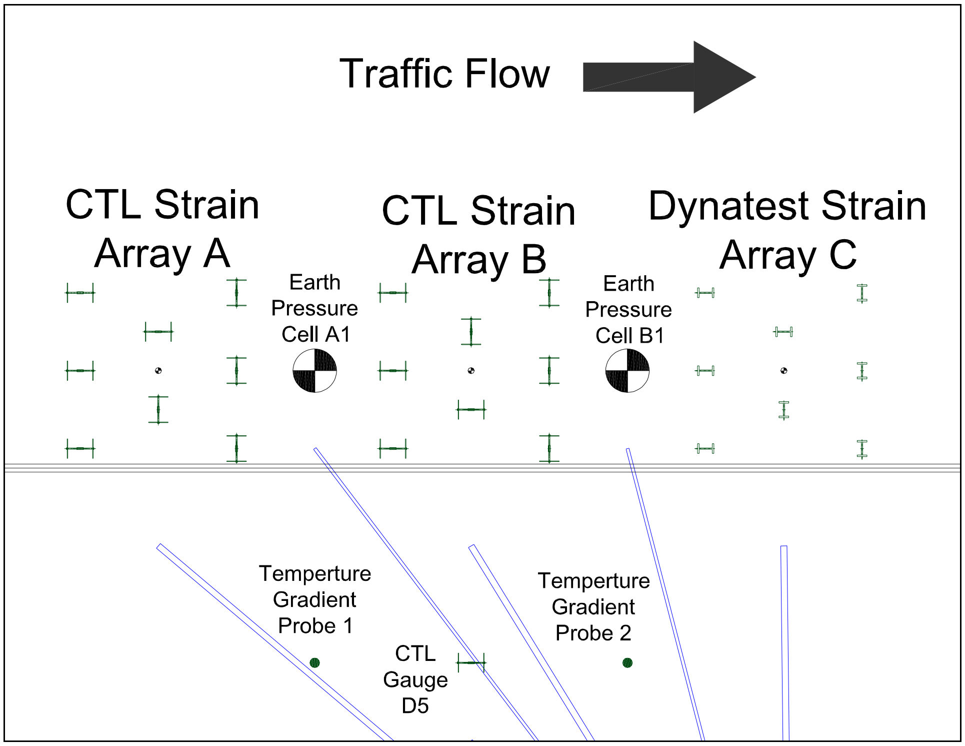

Figure 2-1 - Layout of the three strain gauge arrays, earth pressure cells, and pavement temperature gradient probes.

It is recommended that each sensor group be pre-cast into a thin asphalt stratum measuring 2 ft by 4 ft (plan) by 1 inch or less in thickness using representative paving materials obtained from Payne & Dolan. This embedment will be done by MU-TRC team members in a controlled laboratory environment to ensure the placement orientations of each sensor. These pre-cast sections will then be positioned in the field immediately prior to paving operations which will limit the exposure and maximize the survivability of each sensor. During normal paving operations, each strain sensor will be monitored by the data collection equipment to provide a record of the pre- and post-paving output of each sensor.

2.4 Subgrade and Base Course Pressure

The dynamic load-induced vertical pressures imposed within the base and subgrade layers are related to the performance of these layers, in terms of rutting potential, as well as to the fatigue performance HMA layer. It is recommended that Geokon earth pressure cells be placed within both the compacted natural subgrade and the constructed dense graded base layer along the centerline of the outer wheel path of the outer driving lane. Subgrade pressure cells will be positioned at a depth of approximately 3 inches below the top of the natural subgrade in advance of select material placement. Base layer pressure plates will be positioned approximately 2 inches below the top of the compacted dense graded base layer (upper third-point) prior to the placement of the open graded aggregate base materials. Pressure cells at each elevation will be positioned longitudinally within 5 feet of the leading and trailing asphalt strain sensor groups.

Based on the typical proposed pavement section, the vertical stress anticipated at the elevation of the base and subgrade layer pressure plates due to the self-weight of the paving materials after construction is complete is approximately 1.6 psi and 3.5 psi, respectively. Under severe loading, represented by a 24,000 lb single axle load with a tire inflation pressure of 125 psi, vertical pressures at the elevation of the base and subgrade pressure plates may be expected to increase to approximately 8 psi and 5 psi, respectively. The critical stress conditions for each pressure plate can be anticipated during pavement layer construction when cover materials are minimized. Under these loading conditions, vertical pressures at each elevation will tend towards the inflation pressure of the supply trucks which may be as high as 125 psi. To survive these extreme conditions, it is recommended that the load range of each selected pressure plate be extended to 218 psi, which is the nearest selectable pressure range available which exceeds 125 psi.

2.5 Subgrade Moisture

The moisture level in the subgrade significantly affects pavement response and performance, particularly for moisture sensitive subgrade materials which are anticipated within the North Leg project limits. Even though moisture content variations within the natural subgrade layer are not expected to change significantly during the service life of embedded sensors, it is recommended that moisture content readings be obtained at depths of approximately 3", 12" and 24" below the top of the natural subgrade at two pavement locations coincident with subgrade pressure measurements (See Figure 2-1). It is recommended that moisture probes which provide an output voltage linearly correlated with soil moisture be used to provide the best interface with data recordation equipment. The ECH$_2$O EC-5 manufactured by Decagon is the recommended device of this type which is capable of measuring volumetric moisture contents ranging from 0 to 100% in an operating environment ranging from -40 to 60^{o}C. It is further recommended that subgrade temperature measurements be obtained at elevations and locations coincident with subgrade moisture measurements. The ECH20-TE probe uses a surface-mount thermistor to provide temperature measurements. Additional temperature probes supplied by ROMUS, Inc will be installed to provide alternate temperature measurements at depths coincident with moisture probe elevations.

2.6 HMA Layer Temperature

A thorough mechanistic analysis of HMA pavements requires knowledge of the HMA layer moduli variations due to daily and seasonal temperature changes. It is anticipated that mix design data will be available to accurately describe the dynamic modulus master curve for each constructed HMA layer. However, in-place variations of HMA layer temperature must be recorded, or estimated based on prevailing weather conditions, to allow for accurate fatigue modeling. It is recommended that a ROMUS multi-depth temperature probe be installed at two pavement locations to obtain at HMA layer temperatures at 1 inch increments below the pavement surface. Temperature probes will be installed immediately prior to final surface layer paving and located along the centerline of the shoulder, approximately five feet from the curb line (See Figure 2-1). It is further recommended that HMA surface temperature measurements be obtained with an infrared probe mounted on a mast affixed to the roadside cabinet. The preferred device for this measurement is the Omega OS35-20-5V-250C-12V smart infrared temperature sensor, which uses 20:1 optics and provides temperature measurements ranging from -22 to 1832 ^{o}F.

2.7 Weather Conditions

The prevailing weather conditions, including ambient temperature, relative humidity, wind speed, precipitation, and solar exposure play an important role in pavement performance and predictive equations used for estimating HMA layer properties over time. A single, on-site weather station will be installed along the west leg of the interchange project which can be used to provide comparative values for this analysis. It is recommended that site specific environmental data, including solar radiation, wind speed and ambient temperature be obtained to more accurately record these critical environmental parameters and to allow for both specific analysis as well as validation of virtual weather station models that utilize nearby weather station data to predict site-specific environmental data. Based on a review of available instrumentation that can easily be integrated with the recommended data acquisition equipment, it is recommended that the NRG 110S temperature sensor with integrated radiation shield be used to obtain ambient air temperature measurements. It is further recommended that the NRG #40C 3-cup anemometer be used to obtain wind speed measurements. The #40C is capable of measuring wind speeds from 2.2 to 240 mph with an accuracy of 0.2 mph within the measurement range of 11 to 55 mph. It is also recommended that solar radiation measurements be obtained with an Apogee PYR-PA5 pyranometer sensor. The PYR-PA5 is designed for continuous outdoor usage in an operating environment ranging from -40 to 131 ^{o}F. All environmental sensors will be mast-mounted on the roadside cabinet which houses the data acquisition and WIM system.

2.8 Axle Load Spectra

The intensity and variation of axle loadings over a specific pavement section directly relates to the performance of that section. Weigh-in-motion and static scales have been installed at various locations in Wisconsin; however, none are located close enough to the North Leg site to allow for accurate analysis of pavement loadings over imbedded sensors. To overcome this limitation, iIt is recommended that a quartz piezo-electric weigh-in-motion (WIM) system be installed to provide axle weight data which meets or exceeds ASTM specifications for Type I highway WIM systems. Quartz piezo-electric WIM systems have been successfully used by the Texas DOT and have shown excellent durability and stability. A WIM system of this type is the only feasible, cost-effective alternative which can be directly integrated into the proposed HMA pavement structure. It is recommended that the ECM Hestia WIM system utilizing Kistler Lineas quartz piezo-electric sensors be obtained for this project. The recommended ECM WIM system will be installed within the outer lane only within 25 feet of the embedded strain sensors, as shown in Figure 2-2. The ECM WIM system includes four Kistler Class 1 Lineas sensors and related recordation equipment. Addition items that must be supplied include an inductive loop, roadside cabinet and foundation, and 110 VAC with surge suppression. These additional items will be provided via change order to the Marquette Interchange construction contract.

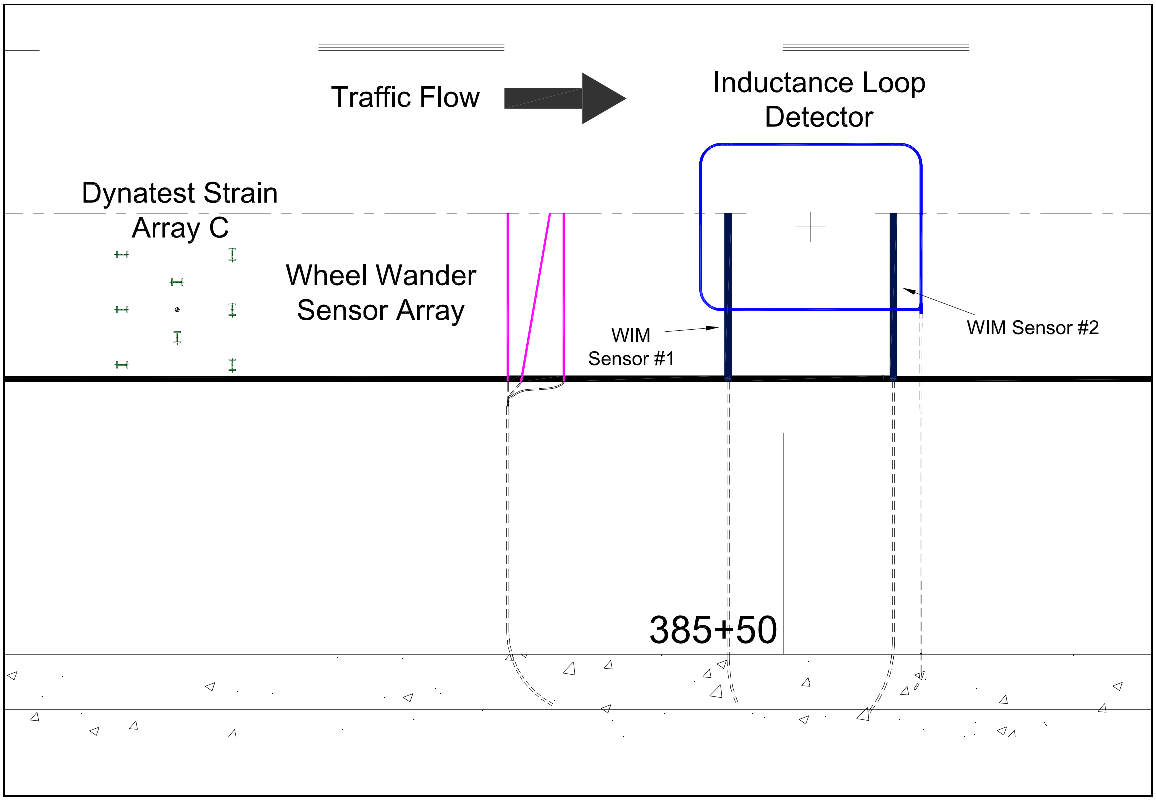

Figure 2-2 – Layout of the WIM and wheel wander systems.

2.9 Wheel Wander

The specific placement of wheel loads in relation to the wheel path centerline or marked pavement edge is directly related to the fatigue performance of the pavement. General models indicate a placement standard deviation of approximately 10 inches may be appropriate. This general model, however, may not be appropriate for the urban setting of the North Leg project and may not allow for the accurate assessment of specific wheel loads on measured dynamic responses. To overcome this deficiency, it is recommended that a piezo strip grid be installed to accurately record the speed and location of each wheel load that passes over the imbedded sensors. This grid will be directly connected to the data acquisition system and will include two transverse piezo strips, each six feet in length, and one angled piezo strip, seven feet in length and spaced an additional 3.8 feet (nominal) downstream from the perpendicular strips. All strips will be positioned across the outer wheel path approximately five feet downstream from the strain sensors, i.e., positioned between the downstream asphalt strain sensors and the WIM system (See Figure 2-2).

2.10 Data Recordation

The pavement sensors recommended for this project can be segregated into slow-speed and high-speed groupings. The slow speed data group includes sensors which record environmental data, including air, pavement and subgrade temperature, subgrade moisture, solar radiation and wind speed. This data will be sampled at rates of 1 Hz or slower with average readings stored at 6 minute increments. The high-speed data group includes all sensors related to wheel loadings, including asphalt strain measurements, subgrade/base pressures, and wheel wander. Sampling rates of 2 kHz will be used to monitor these sensors with all readings stored in a data buffer. Wheel speed data, obtained by processing of the wheel wander signals, will be used to identify data storage "windows" that will be used to store complete traces from each strain and pressure sensor. It is recommended that a National Instruments PXI-6123 S Series Multi-Function data acquisition system be utilized for this project. The PXI system provides for an aggregate of 16 million samples per second with user customized data acquisition boards. The recommended system will include sufficient inputs channels and appropriate data acquisition cards for all recommended sensors and will provide the flexibility needed to monitor, trigger and store data consistent with the requirements of this project.

2.11 Remote Monitoring

It is expected that the products of this research will be of interest to a wide array of pavement designers/researchers who will not have direct access to the project site before, during or after construction. Furthermore, in-service site access may be hampered by the physical constraints of the North Leg project site. To overcome these obstacles, a remote monitoring system will be installed to collect all sensor data via fiber optic lines installed between the roadside cabinet and the WisDOT Traffic Operations Center (TOC). A CCD video camera will also be installed at the instrumentation location to provide a visual record of vehicles/pavement loadings to aid in subsequent analyses and/or data presentations. Data will be transmitted from the TOC to resident computers located at Marquette University via fiber optic or wireless links. The computers recommended for this project include one Pentium 4 class desktop computer and one general purpose Xeon tower server. The Xeon tower server will be equipped with eight hot-swappable 400 GB hard drives. Based on a projected ADT of approximately 150,000 during the initial years of trafficking, it is estimated that approximately 1GB of data will be generated on a daily basis, representing complete traces of all strain and pressure sensors resulting from each and every applied axle loading. The recommended hard drive capacity of 3,200 GB will provide ample storage/back-up space for the data which will be archived at Marquette University and available for downloading by WisDOT and other interested researchers via web-based browsers. A real-time window view of all installed sensors will also be available via the internet. This will provide interested parties worldwide with an invaluable research and educational link to this important project.

2.12 Field Installations

Upon approval of this field installation plan, the MU-TRC team will procure all related equipment and will receive and catalogue all purchases at Marquette University. Verification testing will be conducted on each obtained sensor to ensure all equipment received is in proper working order. The research team will coordinate all installation activities with the North Leg prime contractor and all affected subcontractors to ensure that all project objectives are met without disturbance to normal construction activities. All members of the MU-TRC team will complete the necessary safety training to allow for site access, as needed, during installations.

Imbedded sensors will be monitored during each installation and construction phase to document each system response from as-delivered to post-construction. This record will provide a valuable trace of each device that will be useful in verifying the integrity of the final installed system and/or troubleshooting any problems that may arise. All installation activities will be documented through video and/or still photography and provided in an installation report which will provide a valuable record for potential future installations.

Based on the revised North Leg construction schedule produced on December 20, 2005, initial construction activities of interest are anticipated to begin around April 19, 2006, to include subgrade excavation between Walnut and North Avenue. During this construction phase, subgrade pressure plates, moisture sensors and temperature sensors will be installed by MU-TRC team members prior to the placement of select materials. Aggregate base placement is currently scheduled for the period of May 25 – June 13, 2006. Base layer pressure plates will be installed by the MU-TRC team prior to the placement of open graded aggregate base materials. The WIM detector loop will be installed by Marquette Interchange subcontractors in conjunction with the installation of nearby ramp monitoring loops. Asphalt pavement construction is currently scheduled from July 5 – July 12, 2006. Asphalt strain sensors will be placed by MU-TRC team members immediately in advance of the initial paving operations. Asphalt layer temperature probes will be installed by MU-TRC team members immediately in advance of the paving of the SMA surface layer. The final shifting of I-43 NB traffic is currently schedule during the period of August 1 – 7, 2006. Prior to opening to traffic, and subsequent to final paving operations, piezo strips for the WIM and wheel wander systems will be installed by MU-TRC sub-contract staff. A system calibration and demonstration will also be conducted prior to the opening to traffic.

The construction/installation schedule outlined above is subject to change based on the progress of all work related to the North Leg construction contract. Mr. Nicholas Hornyak, graduate student and MU-TRC team member, has been, and will continue to attend weekly project meetings and will provide regularly updates of the construction schedule as it relates to planned instrument installations. MU-TRC team members will also be in close contact with North Leg subcontractors responsible for pavement construction within the installation area to ensure all related pavement sensors are installed in a timely manner without hindrance to normal construction operations.

2.13 Cost Estimate

The total cost estimate for all equipment specified in this instrumentation plan is $99,710. Of this total, $17,561 relates to equipment necessary to support the WIM system and data transmission from the project site to the TOC. These costs, which are enumerated in Table 2-1, are expected to be paid via contract change orders to the Marquette Interchange construction contract. The remaining cost of $82,149 relates to equipment herein recommended for purchase by Marquette University and paid through WHRP project funds. These costs are enumerated in Table 2-2. It should also be noted that no contingency costs have been included in this cost estimate. While no major additional expenses are anticipated, it may be expected that additional consumable items may be required to support the various sensor installations, material sampling, etc. It is recommended that a contingency fund of approximately $3,000 be established to provide for these miscellaneous expenses.

Table 2-1 – Equipment breakdown and cost associated with WIM system

Item	Item No. (If in 1060-05-71)	Unit	Qty.	Unit Price	Total
1 2 Circuit Electrical Service Meter Breaker Pedestal	SPV.0060.1750	Each	1	$1,052.20	$1,052.20
2 Electrical Wire Traffic Signals 6 AWG	655.0525	L.F.	500	$0.61	$305.00
3 Power Cable Surge Suppressor		Each	2	$200.00	$400.00
4 Base ITS Controller Cabinet	672.01	Each	1	$1,219.30	$1,219.30
5 Install State-Furnished Field Cabinet	SPV.0060.1635	Each	1	$1,113.57	$1,113.57
6 Site Grounding		Each	1	$100.00	$100.00
7 Single-Mode Fiber Optic Media Converter / Ethernet Switch		Each	2	$1,000.00	$2,000.00
8 Single-Mode Fiber Optic Cable		L.F.	2750	$2.65	$7,287.50
9 Ethernet Serial Server		Each	1	$300.00	$300.00
10 Splice Kits		Each	2	$100.00	$200.00
11 Install Conduit Into Existing Item	SPV.0060.1640	Each	1	$53.78	$53.78
12 Conduit Rigid Nonmetallic Sch 40 3-Inch	652.0235	L.F.	200	$3.39	$678.00
13 Conduit Loop Detector	652.08	L.F.	150	$2.71	$406.50
14 Loop Detector Wire	655.08	L.F.	400	$0.48	$192.00
15 Loop Detector Lead In Cable	655.07	L.F.	100	$0.68	$68.00
16 Piezo Sensor Installation		Each	2	$500.00	$1,000.00
17 Piezo Pavement Saw Cut		L.F.	50	$22.00	$1,100.00
18 Piezoelectric Lead-In Cable	SPV.0090.1605	L.F.	100	$0.85	$85.00
19 Miscellaneous					
Total					$17,560.85

Table 2-2 - Cost breakdown of installed project equipment

Item	Recommended Equipment	Unit Cost	Number	Total Cost
Asphalt Strain	CTL ASG -152 Strain Gauge	$ 550	16	$8,800
Asphalt Strain	Dynatest PastII-AC Gauge	$ 650	8	$5,200
Vertical Pressure	Geokon Model 3500	$ 910	4	$3,640
Subgrade Moisture	Decagon ECH2O-TE	$ 200	6	$1,200
Subgrade Temperature	ROMUS Temperature Probe	$ 100	2	$200
HMA Layer Temperature	ROMUS Temperature Probe	$ 250	2	$500
Solar Radiation	Apogee PYR-PA5	$ 225	2	$450
Air Temperature	NRG 110S Temperature Sensor	$ 195	1	$195
Wind Speed	NRG #40C Anemometer	$ 395	1	$395
Pavement Surface Temperature	Omega OS35-20-5V-250C-12V	$ 812	1	$812
Axle Load Spectra	ECM Hestia WIM System	$ 26,500	1	$26,500
Wheel Wander	ECM Piezo Electric Sensors	$ 2,935	1	$2,935
Data Recordation	National Instruments PXI System	$ 24,972	1	$24,972
Remote Monitoring	SDP-1300T Computer System	$ 4,750	1	$4,750
Remote Monitoring	Pentium Class Desktop PC	$ 1,000	1	$1,000
Remote Monitoring	CCD Camera	$ 400	1	$400
Cable Marking	Heat Shrink Labeling	$ 200	1	$200
Total				$82,149

Chapter 3 - Field Installations

This chapter details the processes and methods used to install the instruments mentioned in the field instrumentation plan in the previous chapter. The first section is dedicated to explaining the calibration of the devices that were deemed to require it. The rest of the chapter focuses on the actual installation of the instruments in the field which includes detailed explanations as well as a plethora of digital photographs and diagrams used to illustrate as best as possible the installation processes.

3.1 Pre-Installation Sensor Tests

Before the sensors were actually installed into the pavement structure, tests and experiments were carried on the different types of sensors to test their operability, precision, and accuracy. Some of the sensors used in this project have proven themselves in industry as well as past research, while others have not due to their state-of-the-art status.

In the case where instruments were assumed to be accurate off the shelf, rigorous testing of the accuracy was not conducted. For example, the soil temperature probes were simply placed in two different temperature environments, one room-temperature and one below freezing (inside a chest style freezer), and a calibrated thermometer was placed alongside the probes. The temperature data from the soil temperature probes and the calibrated reference thermometer were both recorded and compared. Similar “spot” checks were done with the various other instruments.

For the instruments where the precision and accuracy was rather unknown, much more involved testing was carried out. The strain sensors were of particular interest because not only are they fairly new to the industry, but their measurement values are very important for this project and asphalt fatigue modeling.

3.1.1 Asphalt Strain Gauges

The horizontal strains within pavement systems can give indications of the type and cause of distresses the pavement structure might endure. A handful of past research programs have used strain sensors made specifically for asphalt and were commercially available. The sensor types used in these programs were typically resistance based strain sensors, although different technology does exist (such as fiber-optic based strain sensors), these types of sensors provide the most accuracy for a reasonable price. Three different brands were most prevalent in these research projects; Tokyo Sokki Kenkyujo Co., Ltd., CTL Group, and Dynatest Group.

The strain gauges chosen for this project were the Dynatest PASTII-AC and the CTL ASG-152 (the Tokyo Sokki Co. was unwilling to divulge information regarding the construction of sensor which they deemed to be a trade secret and would not be easily verifiable and subsequently was one reason they were not chosen for this project; another reason included a poor expectation of anchorage to the pavement structure due to its design). A total of twenty-five strain gauges were proposed for the MI project with three separate groups of sensor arrays. The CTL brand gauges were selected for two of the three arrays (along with one shoulder gauge) while the third array was built with the Dynatest gauges.

In the past and in recent research, these gauges have not undergone (or in some cases, not at all) very extensive calibration. Typically the only calibration provided is from the manufacturer if anything at all. For example, the Dynatest PASTII-AC comes with a theoretical based calibration equation and they specify an estimate for the output of the gauge. For the CTL ASG-152 gauges, they provide a factor that demonstrates the output of the circuit per unit of strain.

Because of this, it was considered important to our research team to examine every possible outlet to get the best understanding of the gauges' in service response. A look back on previous research indicated a presence of some erratic data, thus raising a doubt if the measurements taken are within a reasonable amount of error, let alone true. Since the basis of a "perpetual pavement" is founded on limiting tensile strains in the lower asphalt layer to a rather small amount, it becomes even more important to gain accurate and precise measurements.

Strain Gauge Technology

An explanation on how a strain gauge functions is needed to understand how and why the calibration procedures took the path they did. The subject of mechanics of materials and mild DC circuits is also necessary for the full explanation, and the discussion here assumes that the reader has at least some general engineering background.

To begin, most strain sensors are comprised of a series of very small resistive “strain gauges” mounted to the surface of a material where the strain is to be measured. This report so far has been referring to a strain gauge as the “thing” purchased from the manufacturer (e.g. CTL, Dynatest, etc.). However, these resistive “strain gauges” referred to now are built of a small coil of very thin metal. This coil is then sandwiched in between two layers of a substrate material creating a product that can be adhered to, literally, almost anything (see Figure 3-1). For the duration of this section of this report, the “thing” purchased off the shelf will be referred to as a “strain measuring device” or a “strain sensor”. The strain measuring device is built by using one or more “strain gauges” in a distinctive pattern.

The sandwiched strain gauge package is adhered to the surface of the material in the location of interest (i.e. where strain is to be measured). For example, if we want to measure the strain in a steel bar under tension/compression loaded along its longitudinal axis, the strain gauge would be adhered to the bar’s surface along the longitudinal axis. The adhesion between the strain gauge and the steel rod means that when the rod is subject to loading, the strain on the surface of steel rod is transmitted to the strain gauge. It is theoretically assumed that the strain in this sandwiched package of material is the same strain in the steel bar (although there is a loss depending on the effectiveness of the adhesive securing the gauge to the rod).

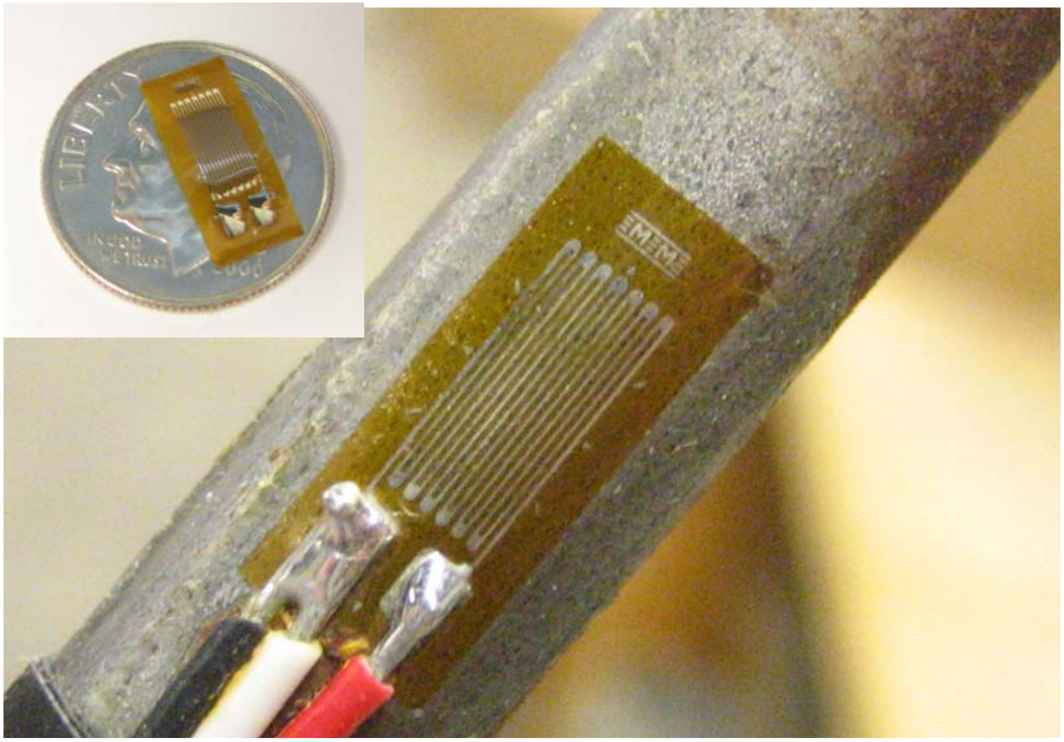

Figure 3-1- Bonded electrical resistance strain gauge mounted to a steel rod.

Nothing has been measured yet at this point. The measurement of strain comes from the relationship of the strain in the steel rod/strain gauge and the resultant change in resistance of the sandwiched metal coils. The foundation of the strain gauge is that there is a strong relationship between the unit changes in resistance per unit change in strain. The relationship is generally given as a gauge factor shown below.

Equation 3-1

$$G = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon}$$

$$\begin{aligned} \text{Where: } & \text{G} = \text{Gauge factor} \\ & \text{R} = \text{Unstrained resistance of strain gauge} \\ & \Delta\text{R} = \text{Change in strain gauge resistance} \\ & \text{L} = \text{Length} \\ & \Delta\text{L} = \text{Change in length} \\ & \varepsilon = \text{Strain} \end{aligned}$$

This relationship is quite simple in theory, in practice however this change in resistance is not measured directly. Samuel Hunter Christie in 1833 developed an instrument to measure unknown resistances. This tool was popularized by Sir Charles Wheatstone and became known as the Wheatstone Bridge. The Wheatstone Bridge can best be described as a DC circuit with four resistors; two parallel circuits containing two resistors in a series as shown below in Figure 3-2.

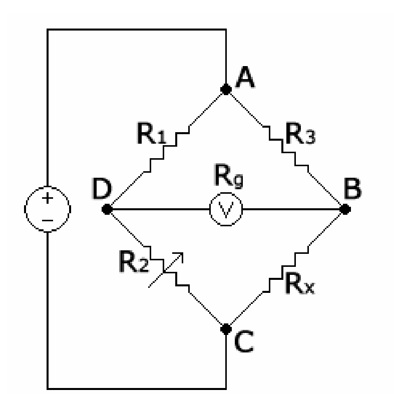

Figure 3-2 - Wheatstone Bridge circuit.

For the purposes of measuring strain, the resistors in the diagram can be replaced with any number strain gauges (actually only one, two, or all four for practical applications). There are multiple arrangements, but the broadest categories are the quarter-, half-, and full-bridge arrangements and, as the names imply, contain one, two, or four strain gauges respectively. The resistor locations in the circuit diagram where a strain gauge is not present (for the quarter- and half-bridge) must still contain resistors to complete the Wheatstone Bridge circuit and is typically done with completion resistors. Completion resistors are similar to any general resistor, except that the actual resistance value is very precise. Typical completion resistors have resistances on the order of ±0.01% of the stated value.

The beauty of the Wheatstone Bridge is that using the laws of circuits, the unknown resistance of the resistors/strain gauges of interest, can be calculated when the other resistances are known (in the case of the full bridge where all of the legs are strain gauges, underlying assumptions are made using elastic material properties (e.g. modulus of elasticity, Poisson's ratio, etc.) to solve for the unknown resistances). The circuit is powered, or excited, across two legs of the circuit with a DC source usually in the range of one to ten volts. The voltage is then measured across the other two legs in the circuit. When all of the resistances in the circuit are equal, the voltage measured across the circuit is zero, meaning that the current flowing through both legs is equal. Remember that voltage is equivalent to the product of resistance and current (otherwise known as Ohm's Law; $V = I \times R$).

After manipulating the involved principal equations of circuits, relationships are created so that strain can be calculated as a function of the measured output voltage and the excitation voltage or vice versa. Luckily most of this measurement and computation is done for us in most modern data acquisition systems, built with user friendly interfaces. Equation 3-2 below is an example relationship for a half-bridge setup for measuring bending strains in a beam.

Equation 3-2 - Half-bridge output equation.

$$\frac{E_0}{E} = \frac{G \times \varepsilon \times 10^{-3}}{2} = \frac{mV}{V}$$

Where: G = Gauge factor (≈ 2 for most applications)

E_0 = Measure voltage across bridge, mV

E = Excitation voltage, V

ε = Strain, $\mu\varepsilon$ (micro strain)

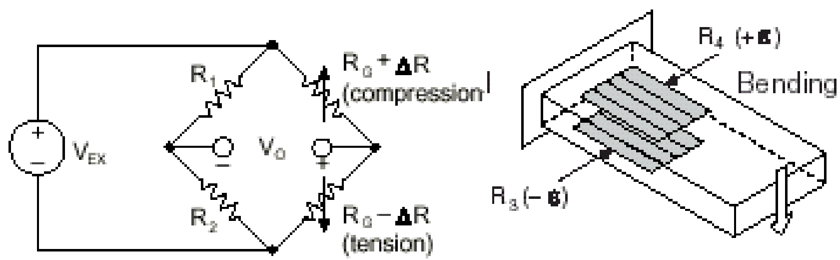

Figure 3-3 - Circuit diagram and physical arrangement for the half-bridge circuit.

From the above equation, if we have 1000 με with an assumed gauge factor of 2, we will get an output voltage ratio of 1 mV/V. Now if the excitation voltage is 10 VDC, the measured output of the Wheatstone Bridge will be 10 VDC. This relationship can also be rewritten to calculate strain as a function of the voltage ratio (E_0/E) and the gauge factor.

One obvious point to understand is that, for a given amount of strain, as the excitation voltage increase, so does the measured voltage across the bridge. In other words, we can generate a larger amount of voltage change in the bridge by increasing the excitation voltage. Remember that it is voltage that is being measured by the data acquisition system and even though it has the ability to measure down to the microvolt, the bigger the change in voltage per unit of strain, the more precisely the strain can be measured. Accuracy of the measurement will come from calibration.

It may seem too good to be true (and it is) that precision can be increased by merely increasing the excitation voltage. High excitation voltage causes excessive heat generation witch degrades the effectiveness of the gauge. Strain gauges have resistance and current flowing through them which causes an energy loss, thus the reason for the voltage drop across the arms of the bridge. This energy loss comes in the form of thermal energy which must be conducted away from the gauge through the substrate, adhesive, and finally into the surface which is it mounted. Higher temperatures tend to disrupt the self-temperature compensation built into the gauges and also affect the zero (balanced circuit) stability. From Ohm's Law we can calculate the power generated in Watts by the following equation.

Equation 3-3

$$Power = \frac{V^2}{R}$$

$$\begin{aligned} \text{Where:}\quad & \text{Power} = \text{Power generated by resistor, Watts} \\ & \text{V} = \text{Voltage, Volts} \\ & \text{R} = \text{Resistance, Ohms} \end{aligned}$$

To measure strains in an asphalt pavement, these concepts need to be combined into a package that can be installed into the structure. For typical applications the first step is to select a suitable bridge type and gauge arrangement pattern for the application. For instance, certain gauge arrays/patterns will reject bending strains imposed on the object and will only measure axial strains. Next the proper strain gauge size, resistance, and composition are selected to match the required sensitivity and also the material that the gauges will be adhered to.

With these properties selected, the gauges need to be adhered to something. Whatever is selected must be able to be placed into the asphalt and must be securely anchored within the asphalt layer. The device must be able to transmit the strains in the pavement into the strain measuring device where the individual gauges are mounted. In other words, the strain in the device must match the strain in the surrounding asphalt. If this does not happen, pavement strains cannot be measured accurately.

Because of this, most strain gauge measuring devices typically take the form of an “H” or “I” shape; having a smaller mid-section with large anchors attached at the ends. The strain gauge bridge is mounted in the middle of the mid-section. This device must be relatively similar to the pavement in terms of stiffness in order “follow” the strain in the pavement. Any disruption to the stress field in the pavement will result in inaccurate measurements. For example, a large, very stiff device would act like steel reinforcement in concrete, and the section of asphalt would be reinforced by the device. The amount of stress in the pavement is relatively low, so if a two inch diameter steel bar were installed in the layer, it would be expected that barely any axial strains would be induced in the bar.

A strain measurement device must be designed to be small enough not to disrupt the stress field in the pavement and also must have stiffness close to that of the pavement. A low stiffness is best, but the device must be able to survive the stresses imposed during paving. Keeping these factors in mind, a device for measuring strains in pavement and beyond can be successfully created and implemented.

CTL Group Asphalt Strain Gauge ASG-152

The CTL Group ASG-152 is a full-bridge strain gauge specifically designed for use in asphalt pavements. The gauge is composed of a nylon rod with two aluminum bars threaded onto the ends, forming an “H” shape. The measuring portion of the gauge is located in the middle of the nylon rod and is covered in layers of protective coating, thus shielding the critical components from the dangers of excessive heat, moisture and foreign matter intrusion during installation and service. The sensor leads are made up of four conductor, shielded wire specifically made for high temperature applications.

The strain gauge pattern is set up to measure axial strains along the longitudinal axis of the nylon rod and rejects bending strains. The governing equation for the specific strain gauge pattern is the following:

Equation 3-4

$$\frac{E_0}{E} = \frac{[GF \times \varepsilon \times (1+\upsilon)] \times 10^{-3}}{2 + [GF \times \varepsilon \times (1-\upsilon)] \times 10^{-6}} = \frac{mV}{V}$$

$$\begin{aligned} \text{where}: E_0 &= \text{Bridge Output, mV} \\ E &= \text{Excitation Voltage, V} \\ GF &= \text{Gauge Factor} \approx 2.0 \\ \varepsilon &= \text{Strain, } \mu\varepsilon \\ \upsilon &= \text{Poisson's Ratio (assumed} = 0.38 \text{ for 6/6 Nylon)} \end{aligned}$$

The relationship between strain and the voltage ratio is non-linear as shown above. However this non-linearity is quite small and correction is not necessary for most applications. The disparity between measured strain and actual strain is only about 2% in 100,000 µstrain. When the Wheatstone Bridge is highly out of balance, then correction may be necessary, but for most instruments destruction will likely occur long before large shifts are encountered.

The manufacturer of this gauge provides a data sheet for every gauge they build. This data sheet contains information regarding some quality control measures such as a submersion test and resistance check. A calibration factor is also provided that states the amount of change of bridge output for some given change in strain. The procedure for preparing this calibration factor was unavailable from the manufacturer.

To calibrate this sensor, it was possible to attach a high precision extensometer directly to the nylon rod. The extensometer used, has a precision in the range of one to five micro-strain and has been calibrated using industry standards. The calibration is traceable to NIST standards. The easiest test to calibrate this strain gauge was to essentially support one end of the gauge vertically and hang weights on the other end. Thus causing a constant stress applied to the rod and causing a proportional strain in the rod. The strain in the rod can be measured with the extensometer while the output voltage of the strain gauge can be measured with the data acquisition system.

The strain measured with the extensometer can be taken as the baseline, or "truth" value, while the voltages taken from the strain gauge can be converted to strain through Equation 3-4. These two strain values can then be compared to see how the CTL ASG compares to the reference values. If the material and geometric properties of the gauge can be measured, verification can also be performed by calculating the expected strain using mechanics-of-materials principals.

There are many different factors that make this seemingly simple idea quite complicated. The first and foremost factor that makes difficulty for load testing the gauge is that the bars at the end of the gauge weren't necessarily square to the rest of the gauge. A support was made specifically for the gauge but because the bars weren't square the rod had the tendency to bend slightly under load. This bending taking place in the rod causes extra stresses and strains in the rod that needed to be eliminated.

The extensometer measures strain on the surface of the material that it is attached to. In a similar fashion, so do the strain gauges that make up the instrument, but because of their arrangement, the effect of the bending strains encountered are balanced out. Hence, the particular bridge pattern does not measure bending strains; only axial strain. The bridge pattern rejects bending strains due to the fact that the strain gauges adhered to the nylon rod or mounted 180º apart from each other. Because of this placement the tensile and complimentary compression strains are both measured and are balanced out. The strain gauges only measure when they both undergo the same change in the same direction.

Using the same concept the bending strains were balanced out by running two load tests on the gauge. The pair of tests used the exact same load steps and carried out exactly the same. For the second test, the extensometer was rotated 180º from the position it was at during the first test. The location along the length of the rod was unchanged.

The result was two sets of data that both contained data from the extensometer and the CTL ASG. Since the load steps were exactly the same for both tests, pairs of data from each data set could be combined; the addition of which balanced out bending strains generated during the test. An example of the data pairs and their combination is shown below for one such test.

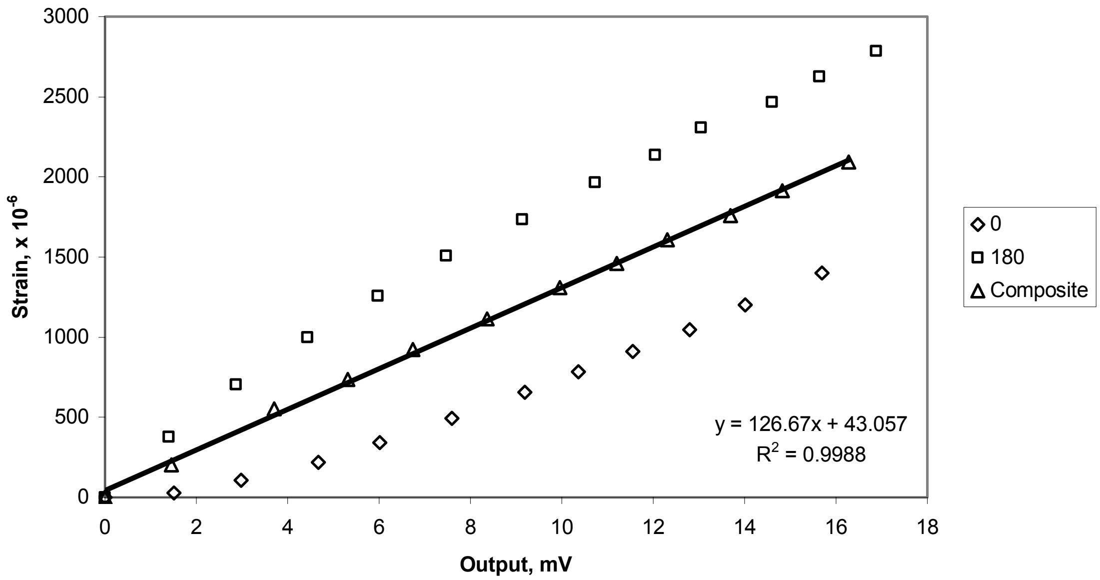

Figure 3-4 - Example of calibration data.

Specifically the data consisted of strain, in micro-strain, from the extensometer and bridge output voltage from the CTL gauge. This data combined with its compliment pair generated a calibration factor which was essentially one number that described unit strain per unit of voltage, thus creating a linear trend. The reason behind choosing this format for a calibration factor was simply to accommodate the setup for the data acquisition system.

This was carried out for every gauge and produced repeatable results. The assumption regarding balancing out the bending strains was further supported by the linear relationships generated after combining the data pairs. A graph of the theoretical strain (using a typical modulus of elasticity) on the same plot with the experimental data, shows fairly good agreement. Any disagreement could be disputed because only a typical modulus value was obtained. A destructive test of the elastic modulus of a similar nylon rod was done with results close to that assumed, but no conclusion on the actual modulus of the nylon could be drawn as the value is inherently variable for all polymers.

A few more issues arose out of final review of the calibration results. Using an approximate Poisson's Ratio of 0.38 for the nylon, an excitation voltage of 5 volts and using the equation above a sensitivity factor can be calculated to be 145.0 με/mV. The sensitivity factors found experimentally and those provided by the manufacturer were much lower at 120.0 με/mV and 110.0 με/mV respectively. This means that the sensors were actually more sensitive than the theoretical calculation and a better look into what was happening needed to be investigated.

Reviewing all possible defects that could have taken place during construction, it is most likely that the gauge factors for the individual gauges are not exactly 2 as stated by the manufacturer. Gauge factors are known to fluctuate significantly between lots and individual gauges themselves. Construction flaws such as misalignment of the strain gauges and errors during the calibration process likely contributed to this effect.

Upon suggestion from associates from NCAT, the effect of temperature on the gauges was investigated. With the gauge connected and taking measurements, the gauge was placed into a freezer. It would be expected the gauge would indicate a decrease in strain due to the contraction of the material from the cool environment. This was indeed the case for a steel rod outfitted with a bonded gauge, but the CTL gauge respond in the opposite manner and actually indicated that tensile strains were being generated.

The reaction due to temperature fluctuations leads to the following conclusions. One property that is widely accepted is that nylon is anisotropic, meaning that its properties are not identical in all directions. The nylon rod used in the sensor has most likely been extruded, which is likely the cause of the anisotropy. This has an effect on the thermal expansion property in that the expansion coefficient is likely different from the longitudinal direction to the circumferential direction. The strain circuit measures strain assuming that the coefficient of linear thermal expansion is the same in all directions, creating the self temperature compensation. This assumption is obviously violated and subsequent calculations can show how this effect occurs and why it causes the gauge to produce tensile strains when the ambient temperature is decreased.

One last issue that warranted investigation was the effect of the non-linear material behavior of the nylon. The stress-strain plot of a typical nylon, or any other polymer for that matter, exhibits a very small amount of elastic deformation with large non-linear stress-strain responses thereafter the linear portion. What needed to be understood was how the CTL gauge would respond under a single load and dynamic loading. Because of the non-linear material behavior it was reasoned that dynamic loading on the gauge could cause strain to "accumulate" because of the additive effect of the permanent deformation. This also brought up a question about how fast the gauge responds to a load and if there are any delayed effects.

To gain insight to both of these issues, nylon rod similar to that used to construct the CTL gauges was outfitted with a quarter bridge strain circuit to measure strain along the longitudinal axis. The ends of the rod were threaded with one end connected to a steel rod. The steel rod was also outfitted with a quarter bridge strain circuit and this assembly would serve as a baseline to compare against. The steel rod had been load tested with the extensometer, used in calibration, to check the accuracy of the bonded strain gauge. The strain measurements from both the extensometer and the bond strain gauge were nearly identical. The elastic modulus of the steel had also been calculated from the load test and agreed with normal values.

The steel and nylon rod assembly was supported vertically and a spring with a weight was attached to the bottom. The weight was then oscillated and the strain from the nylon and steel rods were measured and recorded. The oscillations caused waves in the strain data and what was clearly evident from this test is that the two waves were in harmony which is shown in Figure 3-5. In other words, the peaks and troughs of the strain data matched identically from the nylon and steel rods, thus concluding that there is no delay in the response in the nylon rod.

The second and most important aspect was to observe whether the instrument would accumulate strain over the period of oscillations or remain constant throughout the test. The data showed that there was no accumulation of strain due to repetitive loading. However, only a limited magnitude of strain was generated in the instrument, so it is still possible that much higher loads could cause an accumulation of strain to occur. The amount of strain generated during this test was still much more than was expected to be observed while in service. It should be pointed out the even if an accumulation of strain were observed, in service conditions would most likely push the gauge back to its original position due to its encapsulation in the pavement. This could be checked experimentally by casting the gauges into a block of epoxy or some other material (preferably something linearly elastic) and running more dynamic tests.

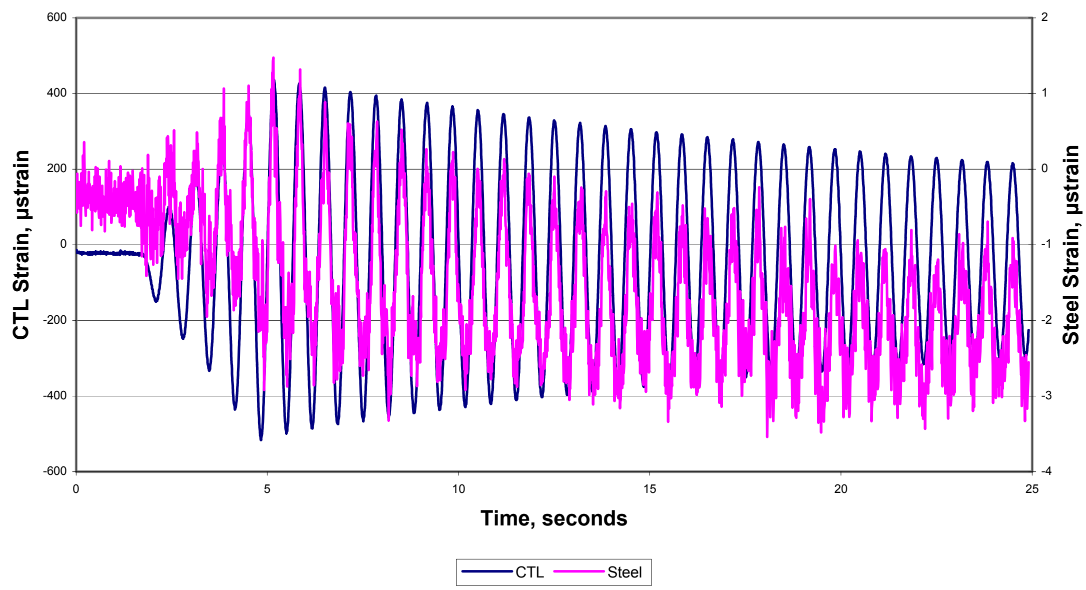

Figure 3-5 - Dynamic response of CTL gauge.

Dynatest PAST II-AC

The Dynatest Group PAST II-AC is a quarter-bridge strain gauge designed for use in asphalt pavements. It is comprised of one 120 ohm bonded electrical resistance strain gauges adhered to a fiberglass-epoxy core. Two stainless steel bars are secured at the ends and act as the anchors for the instrument. The strain gauge and the core are covered in numerous layers of other materials to protect the fragile gauge and de-bond the inner portion of the gauge from the outer portion.

The gauge comes sealed in a wooden box; once opened the warranty is void. The leads from sensor extend outside the box so the buyer can check the resistance across the gauge to ensure functionality. A resistance check of a strain gauge tells the user a few things about the gauge. A successful resistance test of this particular gauge would produce a value near 120 ohms. This tells the user that the leads are connected to the solder tabs on the bonded strain gauge and also that the bonded strain gauge is itself not broken. However, this does not indicate that the gauge is still adhered to its intended base material. This concept also applies to the CTL brand gauges.

As previously stated, this instrument is based on a quarter-bridge strain circuit, implying that only one leg of the Wheatstone bridge is a strain gauge. It only uses one bonded strain gauge that must be placed where strain is to be measured. This requires that the circuit be completed using 120 ohm precision resistors. In the PAST II-AC sensor, the fiberglass/epoxy core is the measuring portion of the gauge and the exact location of the bonded strain gauge and the dimensions of the core are unknown. The governing equation regarding the output voltages and strain is as follows.

Equation 3-5

$$\frac{E_0}{E} = \frac{[GF \times \varepsilon] \times 10^{-3}}{4 + [2 \times GF \times \varepsilon] \times 10^{-6}} = \frac{mV}{V}$$

$$\begin{aligned} \text{where}: E_0 &= \text{Bridge Output, mV} \\ E &= \text{Excitation Voltage, V} \\ GF &= \text{Gauge Factor} \approx 2.0 \\ \varepsilon &= \text{Strain, } \mu\varepsilon \end{aligned}$$

From the output equation, we see that the output per unit of strain is much lower than other strain arrangements and as a matter of fact it is the least sensitive design (least amount of voltage change per unit of strain). This means that the precision at which this instrument can be used to measure is much lower than other gauges. Precision can be increased by using higher excitation voltages, but due to the use of a 120 ohm strain gauge, there is more heat generation.

It is assumed that once installed in the pavement the gauge will undergo only pure tension. The relatively simple design assumes that bending will not occur in the gauge and the manufacturer actually gives blatant warnings that bending will cause damage to the instrument. Unlike other bridge arrangements, the quarter-bridge pattern chosen measures strain wherever the gauge is mounted. The design of the Dynatest gauge is in such a fashion that the bonded strain gauge is mounted near, or on, the neutral axis of bending. This design means that for small amounts of bending the strain generated should be negligibly small or nothing at all.

Due to its construction the Dynatest gauge could not be calibrated by any simple means. De-bonding layers exist between the titanium core and the surface, making it impossible to attach an extensometer to the outside of the gauge and take measurements. These circumstances meant that some other test needed to be devised where the strain in the elements paralleling the gauge could be measured. The first test designed consisted of supports that would vertically connect to the anchors of the instrument and would allow weights to be hung, generating a load. Along with the instrument between the supports, a rod made of different types of materials was attached next to the gauge. The extensometer would then measure strain in the rod which should be identical to the strain instrument.

The first trial had problems with remaining straight during testing, so the second iteration of the experiment was developed using an aluminum beam. The supports from the first design were modified and tightly clamped to the beam. The gauge and a small nylon rod could then be securely placed between the clamps. The clamps, rod, and Dynatest gauge were located at mid-span of the aluminum beam. The beam was then subjected to loading that placed the mid-section under a constant bending moment. This setup allowed for a secure connection between the rod, Dynatest gauge, and the beam. Loading the beam then caused tension in the Dynatest gauge and the nylon rod. The step is shown below.

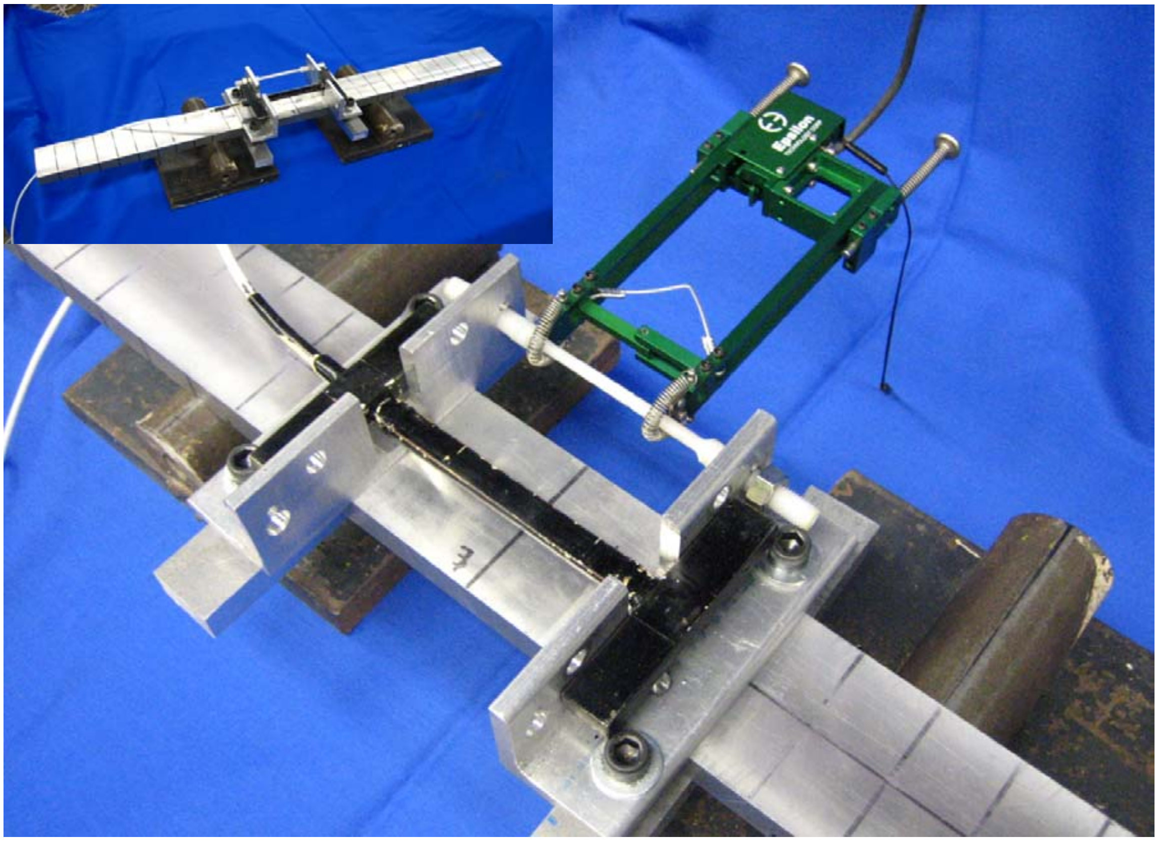

Figure 3-6 - Test setup for calibration of the Dynatest gauges.

The setup itself needed to be calibrated before use. The aluminum angles used to hold the instrument and rod deformed slightly under loading and the deformation was not consistent over the length of the angle. A “mechanical” model of the Dynatest gauge was produced according to the data provided with the gauge. The model and the Dynatest gauge should undergo the same amount of strain when placed under identical loads. This model was put in place of the gauge and two load tests were performed with identical load steps. The strain in the model was measured in the first test and the strain in the nylon rod was measure in the second test. The strain in the nylon rod was then taken as a percentage of the strain in the model. This test was run multiple times and the correction factors from each trial were then averaged.

Once the correction factor was found, a Dynatest gauge was placed into the assembly and a test was performed. The strain in the nylon rod and the output voltage from the Dynatest gauge were measured and recorded. Once the test was complete the gauge was removed, inverted, and reinserted into the assembly and the test was run again. The reason for running the same test on both sides of the gauge will be explained later.

The strain data measured by the extensometer were then multiplied by the correction factor and the result was taken as the strain in the Dynatest gauge. The corrected strains were then plotted against the measured output voltages and a linear relationship was established, the slope of which was the sensitivity factor in terms of $\mu\varepsilon$/mV.

This process was done for all eight Dynatest gauges. In all cases, it was found that the sensitivity, or calibration, factors generated from the paired data were significantly different and the differences were somewhat consistent. Upon further inspection of the gauge, it was noticed that bending the gauge slightly caused a small amount of measured strain. More interestingly the gauge only sensed strain when the instrument was bent in one direction. All of the gauges were inspected in the same manner and bent just slightly and indeed all of the gauges showed that bending on a particular side caused the strain gauge to register a change in strain.

The setup used to calibrate the gauges is based on the bending of a beam, and even though the instrument and nylon measuring rod are placed in the constant moment section of the beam, there is still curvature in that particular section along the beam. This curvature causes some slight deformation to occur in the Dynatest gauges during testing. This bending effect caused a positive increase in strain, which at the time indicated compressive strains. When the gauges were calibrated with this effect active, the net strain measured was actually decreased due to the combined effect of tensile strains being applied but also compressive strains due to the gauge being bent.

The calibration factor was taken as the correct value when the gauge was oriented so the bending effect was not active. When comparing the correct experimental values to the theoretical output based on the above relationship, the values generally agree very well. It should be noted that the excitation voltage used for the Dynatest gauges was 2.5 VDC.

Comparing the experimentally derived calibration data and theoretical conditions based on mechanics of materials is much more difficult to carry out for this particular gauge. The data given for the gauge does include a rough cross-sectional area of the material that the bonded strain gauge is adhered to and also an approximate elastic modulus. The supplied data also includes a relationship that 12 pounds should cause about 1000 με, although this information could not be verified quite accurately. When using the calibration setup, the stresses in the beam can easily be calculated, but because the beam is so small, the composite action of the added equipment changes the moment of inertia of the cross-section and other assumptions, thus disrupting the computations of stress in the beam. If the experiment was carried out again with a much larger beam, then calculations a stress and strain could be calculated while neglecting any changes in the beam's cross-section due to addition of the gauge. A few tests were conducted by hanging weights on the gauges and recording the gauge output voltages. Using the relationship provide by the manufacturer based on load and the expected strain some reasonable data was generated, but with much variability.

The Dynatest gauges were selected for use in the instrumentation project, but most of analyses done would depend on the CTL ASGs with the Dynatest gauges used for comparison. The CTL ASGs would comprise the redundant array of sensors, plus they provide much better precision. Using both brands of sensors allows for a better comparison as their accuracy in measurement of strain has never really been tested, analyzed, and compared. The simplicity of the design of the Dynatest instrument and the results that show a good agreement between experimental and theoretical considerations leads to the conclusion that the gauges measure accurately as stated.

3.1.2 Geokon Model 3500 Earth Pressure Cell

The Geokon earth pressure cell (EPC) is a sensor created to measure pressures applied to its flat circular surface (Figure 3-7). There are a handful of different models all adapted to measure pressures exerted by various materials in any orientation. For this research project, the EPC's will be used to measure vertical pressures due to gravimetric soil and pavement loads in combination with dynamic traffic loads. These particular sensors were selected for this research project based on past use in other pavement research programs (8*, 9, 17*).

Figure 3-7 - Geokon earth pressure cell and Decagon soil moisture probe.

Construction and Theory of Operation

The EPC consists of two thin steel plates that are welded together around their perimeter, leaving a small gap between them. A steel tube welded to the perimeter forms a stem which is open to the volume between the plates. The volume between the plates and the stem are then filled with high stiffness oil that has been thoroughly de-aired. A semi-conductor based pressure transducer is attached to the stem and then enclosed in an outer case, leaving access for the leads. The entire unit is waterproof so it can withstand the environment in which it will be used.

The cells are placed so that the desired stress measurement is perpendicular to the flat face of the plates. The surrounding pressure pushes on the flat plates causing them to deflect, resulting in an increase in the fluid pressure which is then read by the pressure transducer.

The construction and operation of the cells are based on a few assumptions (*19*). The first is that the welded periphery of the cells gives little resistance to the deflection of the plates. Another assumption is that the plates do not deflect excessively under load, which would tend to disrupt the stress field being applied. The last construction related assumption, is that the pressure transducer will deflect little under the applied pressure.

In terms of operation of the cell, it is very important that the instrument itself not distort the natural stress state of the soil it is placed in. This is dependant on two properties; the relative stiffness of the cell (compressibility) and also its width-to-thickness ratio (*19*). For this reason, the cell has been designed to be very thin and its relative stiffness close to that of soil. Because the idealistic state is hard to achieve, over- and under-measurement of the soil stress is likely and is on the order of about ±15% maximum. This error encompasses variations in the stress field due to the cell itself and the soil properties.

Calibration

The model purchased for this project is the Geokon 3500 Earth Pressure Cell (also referred to as total pressure cells, as they will also respond to increases in pore water pressure) which has a 1 MPa pressure range and 0 – 5 volt output range. The specified accuracy of the cells is 0.25% of the full scale value, which is about 2.5 kPa (0.4 psi).

In order to calibrate these devices it was necessary to generate pressures up to the maximum expected stresses, but ideally to the maximum full scale value of 1 MPa (≅145 psi). A pressure vessel filled mostly with water and pressurized with air, was used to generate up to 0.69MPa (100 psi), well above the expected load in the field. Pressure was measured with a pressure gauge possessing an accuracy of ± 0.5% of full scale. The height of water above the center of the plates was measured and added into the total applied pressure.

Testing consisted of putting the plate into the vessel and increasing the pressure in steps while measuring the output of the transducer. The load and output voltage data were then plotted and the data points fitted with a best fit line. It was concluded that the plates performed very well and fell within the manufacturer's specified range. The manufacturer's specified calibration factor is 0.2 MPa/Volt (29.008 psi/Volt). The experimental calibration yielded factors just slightly higher by 0.1 to 0.2% of the given value. Figure 2 illustrates the calibration values obtained during calibration testing compared to those supplied by the manufacturer.

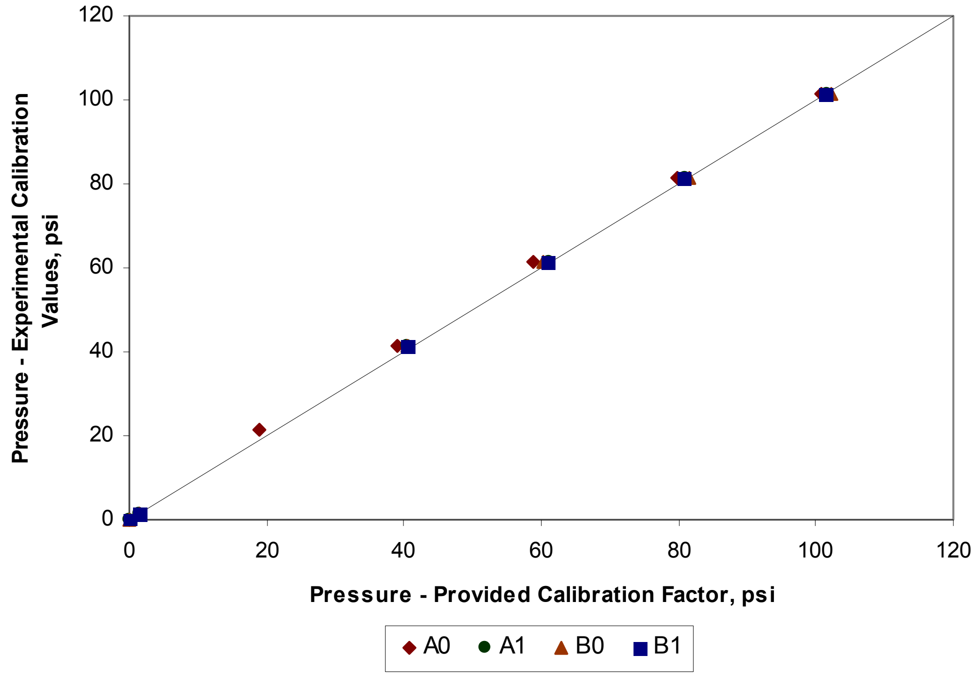

Figure 3-8 - Earth pressure cell calibration data.

3.1.3 Decagon Devices Inc. ECH_2O EC-5 Soil Moisture Probe

The Decagon ECH_20 model EC-5 soil moisture probes are used to monitor the moisture contents of the native subgrade soils in the zone of pavement instrumentations. Typically, soil moisture monitoring instruments work by measuring the dielectric constant or permittivity of the soil. This is done by two different methods. The first, and more popular in recent pavement research, is time domain reflectometry (TDR), where an electromagnetic pulse is generated and the transmit time of the pulse is recorded (8*, 9, 17, 18*). The presence of water slows down the transmit speed. The second method is a capacitance-based process that measures the permittivity of the soil based on the rate of change in voltage across a parallel plate capacitor (directly measuring the capacitance of the soil which is a function of its permittivity). The Decagon

ECH_2O sensors are based on this latter method and are much less complicated to use while also demanding less equipment to run.

The specific model chosen here is advertised as having less influence from factors such as soil type and water salinity. These factors, however small, still contribute to measurement error and calibration is necessary to achieve better performance (*21, 22*).

Construction and Theory of Operation

The EC-5 probes are approximately 5 cm (1.97 in.) long and are composed of internal circuitry enclosed in a fiberglass-epoxy matrix. There are two pointed prongs, which extend from the base and are the measuring portion of the probes (Figure 3-7 - inset). The entire unit is sealed and protected from the environment. During measurement, the probes must be supplied with an excitation voltage between 2 to 5 volts. The output voltage of the sensor is proportional to the volumetric moisture content of the soil.

The manufacturer states that without calibration, the probes are accurate to ±3% volumetric water content. With calibration, the probe accuracy can be reduced to the range of about ±1-2% volumetric water content. It is important to note that these probes, along with TDR based probes, measure volumetric water content, contrary to gravimetric water content. These two properties are related to each other by the bulk density of the soil as shown below in equations Equation 3-6 and Equation 3-7.

Equation 3-6

$$w = \frac{m_w}{m_m}$$

$$\begin{aligned} \text{where}: m_w &= \text{mass of water} \\ m_m &= \text{mass of soil solids} \end{aligned}$$

Equation 3-7

$$\theta = w \times \frac{\rho_b}{\rho_w}$$

$$\begin{aligned} \text{where}: \theta &= \text{volumetric water content} \\ w &= \text{gravimetric water content} \\ \rho_\text{b} &= \text{dry bulk density of soil} \\ \rho_\text{w} &= \text{density of water} \end{aligned}$$

Sensitivity Analysis and Development of Calibration Procedure

The calibration process recommended by the manufacturer consists of mixing soil samples at different moisture contents and compacting the soils into a 30cm x 15cm x 20cm mold (12in x 6in x 8in). The sensor is carefully placed during compaction, with a resulting depth of at least 3cm (1.2in) below the surface of the compacted soil (*6*). It is further recommended that samples from the compacted soil be obtained to determine the bulk density of the soil and its gravimetric moisture content. These values are then used to calculate the volumetric moisture content.

To expedite the procedures, a more efficient process was developed to calibrate the moisture probes. A series of sensitivity analyses were conducted to understand how the probes react to different soils and spatial orientations.

The first test was aimed to understand what the zone of influence of the probe was. This was done by inserting the probe into the surface of a 25 cm (10 in) cube of clay. The outer edges of the clay were then removed in successive

2.5 cm (1 in) increments and the output signal from the probe was observed and recorded. It was noticed that there was a significant decrease in the signal when the clay was reduced to about 5cm (2 in) on each side. It was later found that this effect could be minimized and/or neglected depending on the condition of the free surface of the soil (i.e. the free surface is something other than air).

To help speed up calibrations, reinserting multiple probes one at a time into the same holes was considered. To test this method to see if it was a viable approach, a clay sample was compacted, a probe was inserted and the signal output recorded. The probe was removed and then very carefully reinserted into the cavities already formed. It was noticed that the signal dropped every time the probe was reinserted. Reinsertion of the probe was not a reasonable option and this was later confirmed by the manufacturer. The manufacturer explains that air voids are formed around the probe upon reinsertion which affects the relative permittivity of the soil around it. Another set of analyses also showed that probes cannot be placed within proximity of other probes. The distance at which other probes began to affect the signal of each other was found to be about 9 cm (3.5in).

For the calibration of the probes, it was reasoned that a smaller compaction mold would be ideal for the process. The Harvard miniature compaction mold is a steel cylinder with a height of 7.15 cm (2.8 in), an internal diameter of 3.33 cm (1.3 in), a wall thickness of 0.24 cm (0.1 in), and a volume of 62.4 cm^3 (1/454 ft^3). The volume is constant and relatively small, but still of sufficient size to allow for insertion of the probe. Using this mold for compaction significantly reduces the amount of soil and compaction effort. However, the closeness of the metal wall was in question. A clay sample was prepared, placed and compacted in a large block, but also in a Harvard Mini mold. The probe was inserted into both samples and yielded identical signal outputs. The Harvard Mini sample was then extruded (with the probe inserted) and it was observed that the signal dropped significantly. The extruded specimen, with the probe still inserted, was then placed in a large beaker containing distilled water, so that the water level was just below the top of the soil specimen. The output signal of the probe returned to the same values as before. It was concluded the correct output signals could be generated within the Harvard miniature mold.

Calibration

After the sensitivity analyses were complete, the calibration of the probes began by taking several field samples consisting of silts and clays, crushing down any large clumps, mixing the soil at several different moisture contents in a Lancaster mixer and finally letting the samples sit in airtight containers for 24 hours.

Soil samples were compacted into a Harvard miniature mold by hand using a steel tamping rod. After compaction, the specimen was trimmed and weighed, a moisture probe was inserted, and the output voltage was recorded. The probe was then removed, the soil extruded, and a moisture sample obtained to determine the gravimetric moisture content by means of oven drying for at least 12 hours. Soil samples were prepared at six different moisture contents and compacted using three compaction efforts. For each sample, the dry bulk density and both the gravimetric and the volumetric moisture contents were calculated. A plot of output voltages versus volumetric water content was created for each soil type and probe combination. The trends were in fact all very similar for the different soils and probes. The manufacturer calibration equations suggest a linear trend. They acknowledged, along with other studies, that a non-linear relationship exists between output signal and volumetric water content, especially at high moisture contents (*21, 22*).

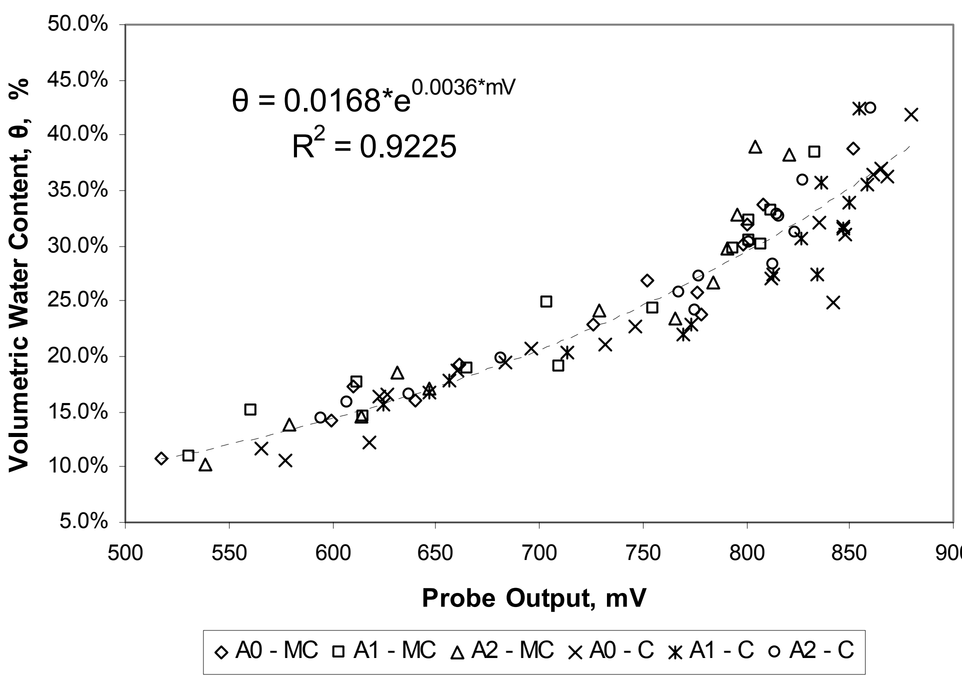

Figure 3-9 - Relationship generated between probe output and volumetric water content (θ) for three probes and two different soil types. The probes and soil type are designated respectively as A0, A1 and A2; and MC (silty-clay) and C (clay).

Due to the reasonably consistent nature of the probes and the specified accuracy of 1-2% with calibration stated by the manufacturer, it was determined that one calibration equation could be used for all probes as shown in Figure 3. The average error between the data and the calibration equation is 2.0%.

3.2 Instrument Installation

This section is dedicated to explaining step-by-step how the specific instruments were installed into their final locations. For instruments such as the WIM system, the installation procedures have already been set forth by the manufacturer with strict procedures, whereas other instruments have much less strict requirements. In all cases the procedures used follow the manufacturer recommended procedures when available.

3.2.1 Sub-Grade Instruments

The equipment that was installed during this operation was the following: soil moisture probes, soil temperature probes, and sub-grade earth pressure cells. The steps needed to complete this step included excavating soil for installation of the native soil instruments, taking density measurements and soil samples of the native soil layers, and finally installation of the native soil instruments.

The native soil pressure plates, moisture probes, and temperature probes were prepared and calibrated well before their scheduled installation target date. However, the installation of these instruments could only be completed after the underdrain for the main line was placed. This eliminated the risk of damaging conduits and wiring from the excavation needed for the underdrain. The underdrain was installed on June 26th and was adjusted days later on June 30th (adjustment was necessary because the drain was installed at improper elevations with areas where the drain was at or near the surface of the select crushed layer). The dense graded aggregate layer was placed around the same time as the underdrain installation.

On July 13th, the sub-grade pressure plates, moisture probes, and soil temperature probes were installed. Two holes were excavated through the dense-graded aggregate and select crushed material at stations 385+16 and 385+26 for the two sensor groups. Upon excavation, it was noticed that there was a slight deviation from the planned pavement cross-section design. When the mainline was being stripped of the existing pavement structure, some cutting below the finish elevation of the native soils was done primarily to remove areas containing some very poor soils. (It was also noticed that there were areas of very damp soil throughout the pavement structure during construction. Very weak sections of the select material could be easily deformed with pressure exerted by a person's foot. Spots that appeared weak, later exhibited signs of pumping of the clay soils up through the select material. These areas were clearly evident as relatively small portions of clay within the select material had worked up to the surface of the select material. They could have been easily mistaken as soil that spilled off a truck or loader as it passed, but closer inspection showed that the material came from the soil layers below.) Due to this over-cutting, the layer of select material was slightly thicker in some areas. This was recognized as a standard construction practice and the variation was merely documented for the purpose of the research. No action was taken to try to correct the issue.

The excavation was cleaned of loose material and further excavated by hand to reach the proper elevations. Nuclear density readings along with soil samples using Shelby-Tubes were taken at the bottom of the excavations. Previously installed conduits were located, cleaned, and trimmed to the desired location. The conduits had been installed by the contracted electricians, Outdoor Lighting.

All of the instruments to be installed were unpacked, cables unwound, and prepared for installation. The bare ends of the wire were protected and pulled into the conduits to the first pull box. The first and deepest instruments to be installed were the Decagon EC-5 soil moisture probes and Romus Inc. soil temperature probes. Where stiff soil was encountered, a Phillips screwdriver was used to create a void that the temperature probes could be inserted. The moisture probes were designed to be pushed into the soil and require this to function properly. A few probes experienced some extra resistance to insertion and required a little more effort to push into the soil.

After each set of temperature and moisture probe was installed (moisture probes were installed with the pointed end of the prongs pointed east and the temperature probes were installed with the end pointing south), the excavation was filled in lifts with the previously excavated material and re-compacted by hand up to the level of the next sensor set. Care was taken to route and cover the vulnerable senor leads to prevent damage to the wires. This involved creating some strain relief in the leads and packing fine soil without rocks around leads. The next temperature/moisture probe set was installed in a similar fashion and soil level brought up to the next level and so on until all temperature/moisture sensors were installed as shown below in Figure 3-10.

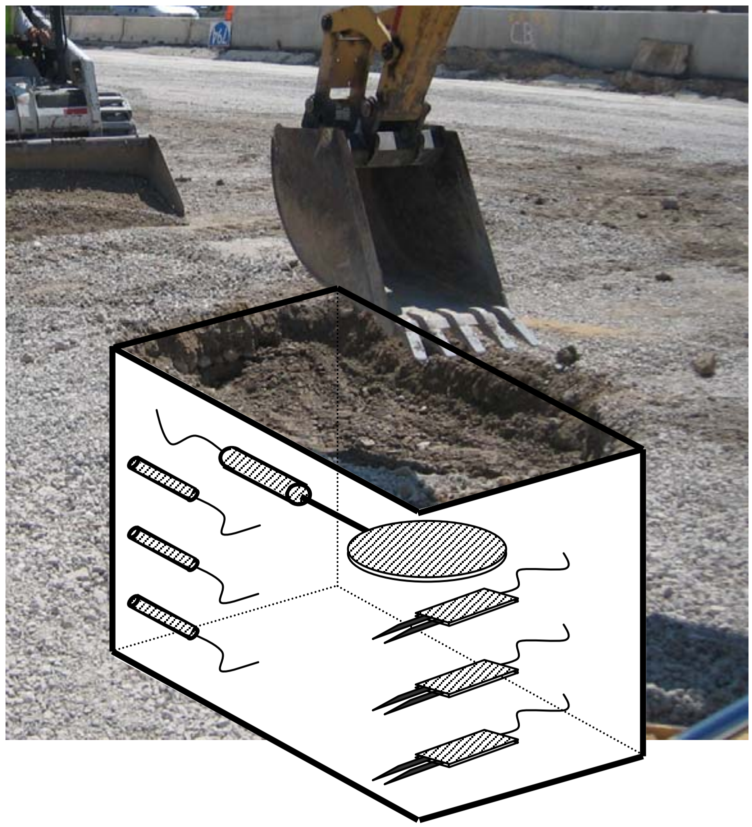

Figure 3-10 - The final arrangement of the sensors after installation. The EPC is aligned so that the sensor leads point into the direction of traffic. All moisture sensors have the pronged end facing east and all temperature sensors have their leads facing north.

All six temperature probes and six moisture probes were installed successfully with target elevations of 3”, 12”, and 24” inches below the top of the native soils. The soil level was brought up higher to the proper elevation for installation of the Geokon Model 3500 Earth Pressure Cell. About a two to four inch thick cushion of densified fine sand was placed over the re-compacted native soils. The sand was then checked for sufficient area, thickness, flatness, and levelness. The pressure cell was then carefully placed and supported on the bed of sand. A level was placed directly on the plate and the supporting sand was reworked until the plate was level in all directions. The location of the center of the plate was measured and recorded with the help of a GPS based surveying locator as shown in Figure 3-11. Once the location was satisfactory, another layer (about two to four inches) of fine sand was placed over the pressure cell and its leads. The sand was densified in layers using the palm of a hand. Once the fine sand was placed, slightly coarser sand from the site was placed and densified (about six inches, see Figure 3-11). It is extremely important to keep large rocks or other large objects away from the instrument. Not only can they damage the instrument, but large objects can disrupt the natural stress field around the instrument. The final orientations of the sensors are similar to that found in Figure 3-10; the final locations of the sensors are listed below in Table 3-1.

Table 3-1- Final locations of moisture and temperature sensors and earth pressure cells.

Sensor	Station, ft	Offset, ft	Elevation, ft	Sensor	Station, ft	Offset, ft	Elevation, ft
Moisture_A0	385+16	33.55 RT	655.0	Moisture_B0	385+24	33.90 RT	654.9
Moisture_A1	385+16	33.55 RT	655.9	Moisture_B1	385+24	33.90 RT	655.7
Moisture_A2	385+16	33.55 RT	656.2	Moisture_B2	385+24	33.90 RT	656.2
Temperature_A0	385+16	33.55 RT	655.0	Temperature_B0	385+24	33.90 RT	654.9
Temperature_A1	385+16	33.55 RT	655.9	Temperature_B1	385+24	33.90 RT	655.7
Temperature_A2	385+16	33.55 RT	656.2	Temperature_B2	385+24	33.90 RT	656.2
Earth Pressure_A0	385+16	33.40 RT	656.6	Earth Pressure_B0	385+24	33.30 RT	656.5

The excavated native soils were replaced followed by the select and dense graded materials, all compacted in lifts. The energy used to densify the materials increased significantly as the distance between the surface level and the instruments grew. The particle size of the select crushed material is on the order of 6-12 inches in diameter, so compaction essentially consisted of placing the first few inches by hand in a dense state. Following this, the rest of the materials were placed in lifts and compacted by dynamic force from the bucket of a backhoe being dropped repeatedly. The possibility of damage to the instruments after the fine sand layers were placed became minimal.

Figure 3-11 –Top: Placing EPC in a bed of fine sand and routing sensor cable carefully. Bottom left: Measuring and recording the final location of the EPC with a GPS based measuring device. Bottom right: Backfilling against the EPC with sand.

Measuring the electrical resistance of the instruments is a quick and easy way to verify the sensor's operability. This can readily indicate whether or not a sensor has survived the installation process (installation carries most of the risk of failure - broken leads being the most common problem). After installation was complete, resistance checks with a general purpose multi-meter were made and indicated that all the installed sensors were functioning properly (i.e. the resistance showed that the circuit was not open). Subsequent field monitoring showed that all sensors were in good working condition and provided logical data.

3.2.2 Base Layer Earth Pressure Cell

The installation base layer earth pressure cells (EPCs) had been delayed until just prior to paving of the first asphalt layer. This was done to reduce the probability of the equipment being damaged due to passing traffic and other construction operations. The final location of the base layer EPCs was just inches below the surface. Because of this decision, the EPCs were installed the same day as the asphalt strain gauges in two separate operations which took place on August 7th 2006.

The dense graded base layer earth pressure cells were installed in a manner quite similar to the plates installed in the native soils. The conduits placed prior were found using the GPS surveying locator device. The open graded, and some of the dense graded, base layers were then removed, exposing the conduits. An area large enough to contain the EPCs was cleaned out and the approximate proposed elevation was brought up with fine sand. The plates were placed on the sand and the elevation to the center of the plate was checked. Adjustments were made to the bed of fine sand until the elevation of the plate was suitable and the plate itself was level in all directions.

After the checks, another layer of fine sand was placed on top of the plate and carefully densified using the palm of a hand. The dense and open graded base layers were replaced and re-compacted using a hand operated tamper. All procedures for installing the plates followed the manufacturer's instructions provided with the instruments. A few important steps for installing the pressure cells are shown pictorially in Figure 3-12.

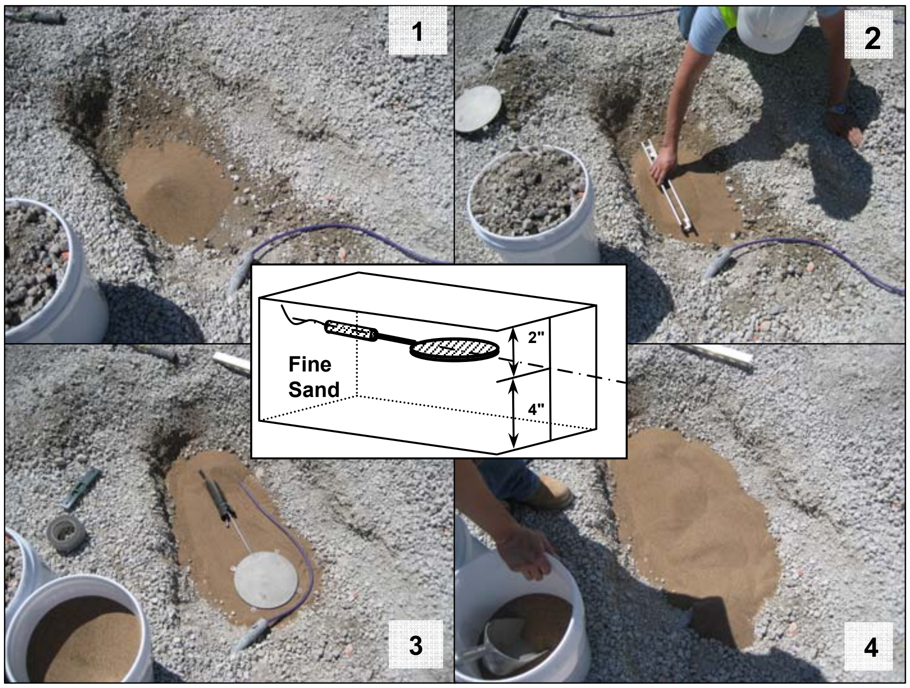

Figure 3-12 - Steps in installing EPC. 1) Filling the cleaned excavation with a bed of fine sand. 2) Leveling the sand out and preparing for EPC placement. 3) Leveling the cell and routing the sensor lead in a safe direction. 4) Backfill against the cell with more sand which would then be followed by the pre-existing base material, compacting each layer by hand. The inset sketch shows the layout of the sensor schematically.

3.2.3 Asphalt Strain Gauges

As stated before in the previous section, the asphalt strain gauges were installed the same day as the earth pressure cells. The first layer of asphalt was scheduled for placement in the test section during the late afternoon of August 7th 2006. During paving strain and pressure data would be recorded throughout various paving operations such as asphalt placement and compaction.

Through meetings with the paving contractor, the paving crews would be crossing the test section during the mid to late-afternoon hours. The median-shoulder and passing lanes would be paved first followed by the shoulder and the lane adjacent to it. Paving started at the Fond du Lac overpass and extended to North Avenue. The placement of the asphalt would follow standard procedures which included dump-trucks backing up to the asphalt pavers and dumping their load while the paver progressed. This presented a problem for installation of the asphalt strain gauges since the gauges could not be driven over by dump trucks supplying the paver with material. Luckily a transfer vehicle was available from the paving contractor which allowed paving to continue without having to drive over the test section (and the sensors). This change allotted more time to arrange and prepare the gauges and is likely a necessity for these types of instruments.

The first step for installation of the ASGs involved finding the previously installed conduits and exposing them. The proposed locations and spacing (see Figure 3-13 and Figure 3-14 below) of each strain gauge was marked on the open graded base layer with paint. The leads on the ASGs were unwound and readied for pulling into the conduits. One team would work on pulling the leads to the bottom pull-box and screwing them into the terminals on the data acquisition system while another worked on preparing the gauges for placement into the asphalt layer.

The cabinet for the project had not been placed at this time, so after the operation was done the wiring for the sensors was left inside the lower pull-box. It was protected from the elements as best as possible. A permanent power supply had not been installed yet either, so a gas powered generator was used in conjunction with proper surge protection to power the computer systems needed for data recordation during the installation.

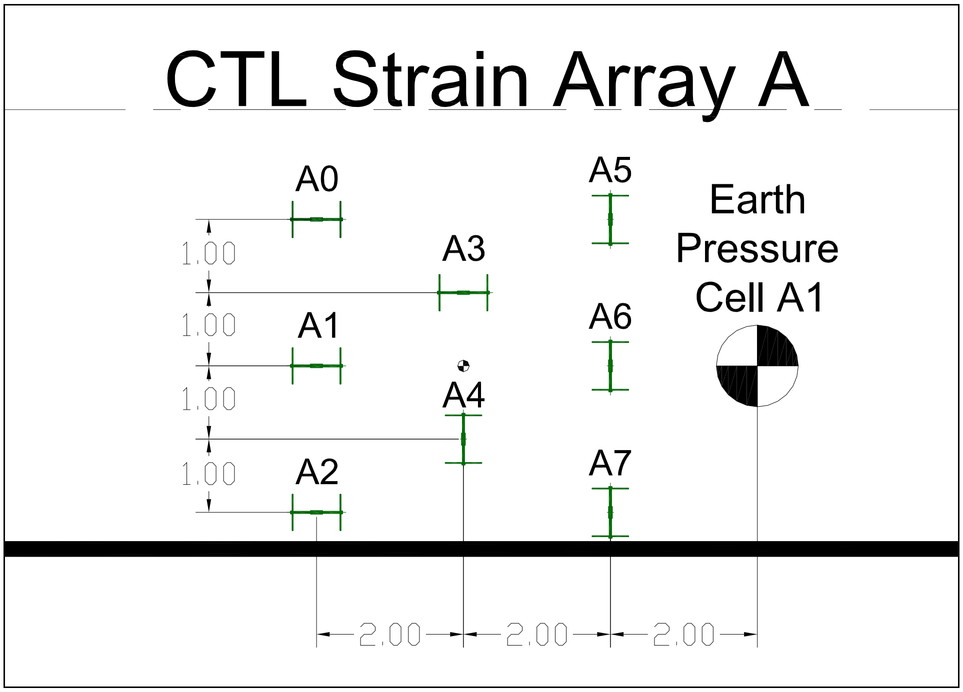

Figure 3-13 - Spacing of the strain gauges and earth pressure cells are shown above. All units are in feet. Note that the orientation of the two gauges in the middle of the array alternate rotation angles (transverse vs. longitudinal) for the two CTL arrays as shown in Figure 3-14.

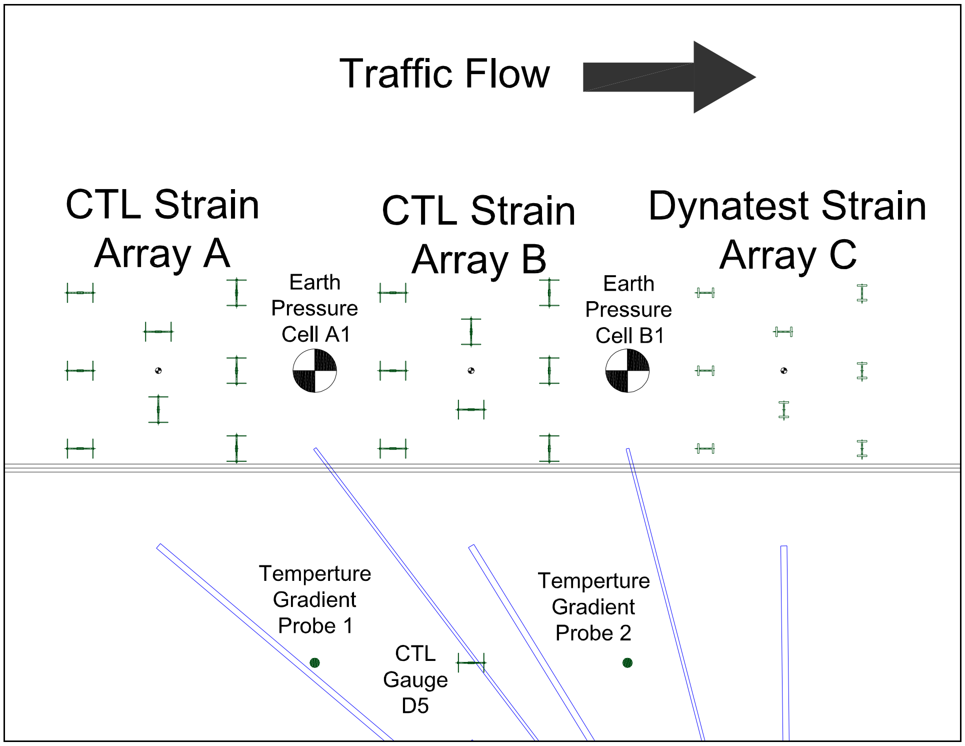

Figure 3-14 - Final configuration of strain gauges, earth pressure cells, and pavement temperature gradient probes.

The locations of the ASGs were checked again and re-marked as necessary. A pre-mixed matrix of sand and binder (the same binder used in the lower asphalt layer mix) was re-heated and brought from the lab into the field. This was placed in a ½ inch thickness on the open graded base layer in the location of each sensor and served as the base pad that the ASGs would sit on. The ASGs were then placed on their respective base pads and the leads were organized and buried into the open graded base layer shown in Figure 3-15. The cable armor installed on the exposed length of the leads protected the wiring from puncture from the sharp stone edges during placement of the asphalt. The ASGs were placed so that the leads exiting the protected portion of the gauge did so against the direction of paving; otherwise forces and motions generated by the paving equipment may have a tendency to pull the sensor leads away from the strain gauge, destroying the gauge. Strain relief was provided multiple times, but survival of the gauges was a priority and every precaution was taken to prevent foreseeable damage.

Figure 3-15 - Left: Marking the proposed locations of the gauges. Right: Placing sand/binder pad and fitting gauges.

At this time it was noticed that some of the Dynatest strain sensors had curled from their original shape. The curled shape was that of a frown, i.e. the center portion of the H-shape was lifted off the asphalt pad. A note was made of the observation along with some small repositioning. Curling of the gauges may have been due to the gauges' multi-layered construction along with the heat from the asphalt material underneath the gauge. This may have caused some temperature differential causing a curling effect similar to that of a concrete slab. The coefficient of thermal expansion for epoxy resins is significantly higher than steel, so this conclusion is reasonable.

Just before the paver was about to arrive at the gauges, asphalt material from the paver hopper was screened off on the 3/8" sieve and placed on the gauges, roughly 1 inch thick. The material was compacted using mild compaction force using a hand tamper. Once all of the gauges were covered with screened asphalt, the gauges were checked once more for sensor leads that were misplaced. A layer of unscreened asphalt (about 2 inches thick), was placed on top of the gauge arrays and compacted using a gas powered plate tamper shown below in Figure 3-16.

Figure 3-16 - Left: Placing screened asphalt on top of gauges and carefully compacting. Right: Compacting the unscreened asphalt over the gauge arrays with the paving crew approaching.

After this was complete the paver laying the shoulder passed over the strain gauge located in the shoulder of the roadway. It was noticed that the left track of the paver traveled over the edge of the covered strain array, but did not run over any gauges. Due to the highway geometry, the lane-shoulder construction joint fell on the right side of the ASG arrays. Since the shoulder and the adjacent lane were paved at the same time, it should have no effect on the functioning of the gauges. The adjacent lane placement occurred seconds after the shoulder placement and covered all the strain arrays completely. The right track and tire of this paver traveled just right of the center of the arrays. It is likely that this put the gauges under a fairly high amount of stress and demonstrates a difference between instrumenting real-world pavements and typical closed circuit test tracks.

The strain gauges were monitored during paving and rolling. Nuclear density measurements of the pavement at two different locations were taken after final rolling. It was noticed during testing that a few of the gauges were not reading properly. Initially it was not known if it was due to damage to the gauges themselves or because the anticipated values of strain were too large for the software setup created for the data acquisition system. It was expected that some large values of strain would be measured since the gauges would be exposed to not only large stresses, but also extreme temperatures which affect the material properties of the gauges and the output of the sensors. Over the progressive paving operations various testing procedures were carried out and any non-functional or poorly functioning gauges would be discovered during those tests. The initial appearance of the data taken shows that all of the gauges were functioning with the exception of one Dynatest strain gauge (Gauge ID – C6).

3.2.4 Inductance Loop Detector

Soon after the first asphalt layer (C2 mix; four inch total thickness) was placed, the second layer (E30 mix; seven inch total thickness) was constructed in two lifts (four inch lift followed by a three inch lift). The loop detector for the weigh-in-motion system was installed between the two E30 lifts; the placement of the sensors can be seen in Figure 3-17. Some testing and checking of all sensors was completed beforehand.

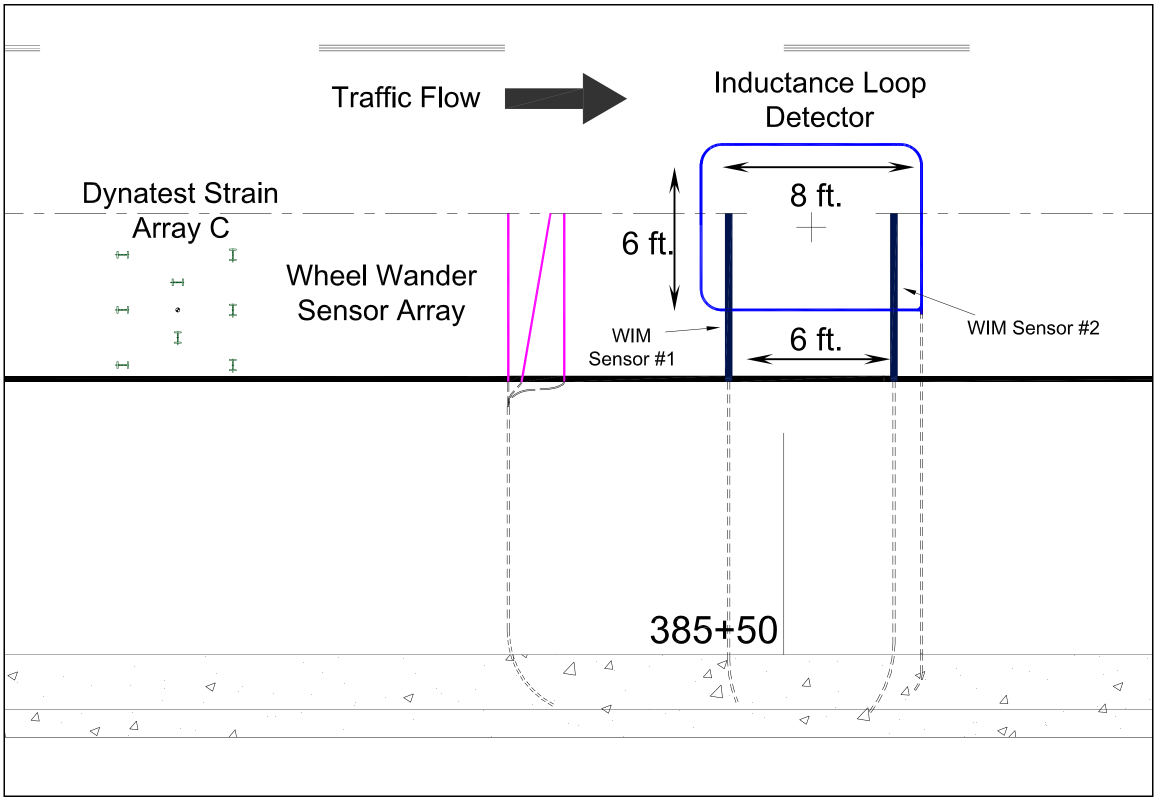

Figure 3-17 - Layout of the WIM sensors (loop detector and two quartz piezo strips) and the wheel wander sensors. The conduits installed into the pavement are also shown as hidden lines extending from the instruments to the curb.

The second lift of E30 was scheduled for placement on August 9th 2006, however due to inclement weather it was pushed back until the following day. Paving started on the inside lanes first and worked towards the outer lanes similar to the pattern used during the first layer. Two lanes were paved simultaneously with two different pieces of paving equipment.

The inductance loop detector was positioned and readied for paving. Instead of using a traditional inductance loop detector, a Never Fail Loop Systems Inc. loop was used instead. This was done because as the name implies, it has a very low risk of being damaged and comes with a 10 year warranty. The loop wiring is encased in rigid conduit sections and filled with bitumen, thus protecting the inside and maintaining its shape. The leads running from the loop to the roadside conduit are also protected in a rigid cable sleeve. This level of protection means that it can be driven over by construction equipment reducing construction interference. Further more, since it is being paved over and into the pavement structure, there is no need to come back and saw-cut the new pavement to install the sensor. The loop is pre-assembled as a single unit; installation required nothing more than laying the unit out on the pavement, pulling wires, and securing it in place - the loop installation required no extra specialized help or tools to install.

The inductance loop was secured to the pavement using a fiberglass adhesive-backed tape (known as “Gorilla Tape” manufactured by the Gorilla Glue Company) shown in Figure 3-18. The tape is similar in appearance to standard duct tape, but much stronger and has much more adhesive strength (it should be noted that metal should not be used in close proximity to the loop detector as it may deteriorate its sensitivity). Sections of the loop were secured in multiple locations and the wires were pulled to the conduits and secured. A simple resistance and continuity check of the loop after placement showed that the wires had not been broken and the sensor should be operational.

Once the loop was secured in its proper location, the paving crews simply needed to pave over the loop. However, on most pavers it is important to note the scraper that is located in front of the tracks/tires. Its purpose is to scrape any spilled asphalt out of the track/wheel path to promote smooth advancement of the paver. However, it must be raised out of the way when dealing with any instrument leads crossing the path of this scraper. Failure to do so will result in damage to the instruments.

Figure 3-18 - Pictures showing various parts of the loop detector installation. Top: The fiberglass tape was hammered lightly to create a good bond to pavement. Bottom left: The asphalt around the conduit was removed with a cold chisel and hammer to expose enough conduit to install a "homemade" 90° elbow. The rather thick looking orange cable actually ends just inside this elbow and only two small wires actually pass through the elbow. Bottom right: A close up showing how the corner was adhered to the pavement and also the construction of the Never Fail Loop.

The paving train approached and construction proceeded as normal. A quality control technician of the paving company was there taking density measurements of the freshly rolled asphalt. Two separate nuclear density measurements were made at two different elevations. These values were recorded for future research purposes.

3.2.5 Equipment Cabinet

The roadside cabinet had been installed on its concrete pad (Figure 3-19 shows the project cabinet in place) by Outdoor Lighting and since the system was close to being complete, most of the equipment was prepared to be installed into the cabinet. This work was done while waiting for the paving crews to reach the test section with the final SMA surface layer so the temperature probes could be installed. Many of the sensor leads (including moisture probes, temperature probes, strain gauges, etc) needed to be extended to reach the inside of the cabinet (a "comfortable" distance from the lower pull-box into the cabinet is about 20 feet). The data acquisition system, din-rails, power supplies, wireless radio, weather/antenna mast, and pavement temperature/camera mast were installed during this time period.

Once all of the wires were pulled into the cabinet they were connected to their appropriate terminals on the data acquisition system. One component of the system which was not installed was the controllers for the WIM system. The WIM controller would be installed with the WIM sensors which required factory certified installers.

The mast containing the environmental sensors (air temperature, anemometer, and pyranometers) and wireless antenna was fitted to the cabinet first and then brought back to the shop at Marquette and properly outfitted with the instruments. The bottom of the mast is supported by a "street" elbow which connects the hollow mast tube to the inside of cabinet. The wiring for the mounted equipment enters into the mast via ports and through the elbow into the cabinet. The mast was sealed as best as possible to prevent moisture from entering the cabinet.

The mast supporting the camera and infrared thermometer is made up of PVC conduit attached to the column supporting the sign structure. A ball-and-socket joint was constructed for the infrared temperature probe and the camera came outfitted with its joint; both instruments have a wide range of adjustment range.

The leads for these two instruments take a non-direct path to the instrument cabinet. The wiring runs into a stainless steel box mounted to the east side of the column. This box has its own access panel and was originally intended for the sign-bridge equipment. The instrument leads have a splice inside this box allowing them to be easily disconnected. From this box, the leads travel to the WisDOT ITS cabinet and finally into the project cabinet. This seemingly complicated wire routing is due to a deviation from the original plans.

Figure 3-19 - The highlighted cabinet is occupied by the equipment for this project. The mast connected to the cabinet holds environmental sensors as well as the wireless communications antenna. The cabinet in the background houses various traffic control devices for WisDOT. The two cabinets are connected by a limited number of conduits.

3.2.6 Wireless Antenna

The wireless antenna system is comprised of antennas at the roadside cabinet and on the roof of Carpenter Tower Hall at MU. The antenna at the roadside cabinet had already been installed, but the wiring in Carpenter Tower Hall required much more work to complete. The antenna is located on the northwest corner of the roof, as shown in Figure 3-20, with the wiring running from the antenna into an access hole on the upper level of the roof. The wire was then strung through the floor and into the corner of the room below adjacent to the data drop provided by Marquette's IT staff. A shelf was provided for the wireless modem at that location.

The coaxial cable that the antennas used for signal transmission required that special connector be installed. Service personnel from TAPCO Inc. installed the terminals on the cables on September 21 and the cable modems were powered up and checked for connectivity. The results showed that the connection was excellent even though the line of sight from Carpenter Tower Hall to the test section is blocked by grain elevators from the now defunct Pabst Breweries. The line of sight is visually shown in the right photograph in Figure 3-20.

Figure 3-20 - Left: The wireless antenna mounted on the corner of Carpenter Tower Hall at Marquette. Right: View from the antenna location at Carpenter Tower. The test section is located just behind the grain elevators in the highlighted area.

3.2.7 Pavement Temperature Gradient Probe

The original schedule for the installation of the temperature probes was the night of September 8th 2006 and into the following morning – most of the cabinet equipment was installed during this time as explained above. However due to unknown reasons, paving stopped during the night and the temperature probes were not installed.

The project contractor needed to open the highway to traffic on the morning of the 15th to avoid penalties and final paving of the final wearing course in the test section occurred in the early morning of September 14th. Installation of the two pavement temperature gradient probes proceeded as expected.

The installation of the probes consisted of a few, but relatively easy steps. The first step was to locate and expose the previously installed conduits. The second step is to determine the location of the probes and drill the appropriate sized holes that the probes would be inserted into. It was very important to drill only to the required depth so the probe didn't settle below the desired elevation. The probes used here actually protrude from the surface of the existing pavement about one inch so that the upper portion of the probe is embedded within the two inch thick SMA layer. The holes and channels for the sensors were cleaned and the sensors were dry-fitted into final locations, making adjustments as necessary.

The sensor leads were pulled almost all of the way into the conduit. Since the conduit opening was close to the curb, the sensors were pulled off to the side of the roadway until the time approached to pave over the sensors. When paving crews approached, the temperature probes were pushed in the drilled hole until they bottomed out. The protruding end of the probe was re-measured to ensure that the probed would not be higher than the final pavement elevation and actually was designed to be one-half to one inch below the surface of the SMA as shown in Figure 3-21. After this check the sensor leads were fitted into the channels and the excess wire was pulled into the pull box. Sealant was then placed in the channel to secure the wire into the channel and also protecting it from the approaching paving equipment.

Figure 3-21 - The photograph on the left shows almost the entire length of the temperature probe. The photograph on the right shows the temperature probe fully inserted to its final position. Note that the sensor lead is fitted into its channel, but has not been sealed yet.

The next step consisted of watching the paving equipment pass over the sensor. Because of the location of the sensor on the pavement and the procedure used to place the SMA, the protruding temperature probes fell within the wheel base of the trucks charging the paving equipment. Again, it is warned to pay close attention to the scrapers in front of the paver's wheel path (see Figure 3-22) because it has the potential to destroy the sensor leads. They can be (typically) easily lifted up and secured with chains (usually welded right to the paver).

Figure 3-22 – The scraper in the wheel paths of the pavers should be lifted off the pavement surface to avoid destroying sensors and their wiring. The inset picture is a close-up of the scraper which is in the down position, resting on the pavement surface.

After the material was placed and rolled the pavement surrounding the probes was inspected and appeared unaffected by the protruding probes. The installation of the temperature gradient probes was successful up to this point, but the sensors still needed to be checked to see if they were operable. During the installation the sensors were connected to the data acquisition system and seemed to produce logical values, however one probe was producing erratic data and it was determined that it was due to a shortage of power and would simply require another power supply.

3.2.8 Wheel Wander and Weigh-in-Motion System

The wheel wander piezo strips and the weigh-in-motion (WIM) sensors were installed at roughly the same time. These sensors are both installed into the SMA surface layer and required the use of two nighttime lane closures to complete the installation of both. The first few steps in installing the sensors are quite similar.

The first night of work included laying out the exact locations of the sensors, saw-cutting and chipping out the channels. Layout of the sensors was done by two separate methods. The first was done by using a series of reference points on the curb line to triangulate the ends of the conduits located within the asphalt. The other method used involved using the GPS location tool to find the ends of the conduits. Both of the methods produced locations that were very similar and proved to be accurate when actually removing the asphalt.

Once the ends of the conduits were located and marked, the layout of the proposed sensor locations were done so that the sensors were perpendicular to the edge stripe painted on the pavement as well as the curb. No drastic difference in these two layout references was found. It was very important that the layout dimensions be as close as possible to that proposed in the original plans, but slight deviations were inevitable. The final locations of the sensors were measured and recorded so that any adjustments or calibrations to the system could be made.

Once the layouts were finished, the channels were cut with a wet-cut diamond blade. It was very important that the cuts were made precisely due the limited volume of grout available for each sensor. Once the saw-cutting had been finished, an electric Hilti chipping hammer was used to the cut out the asphalt. For the WIM slots, the entire SMA layer was removed down to the layer below, which made chipping very easy. The wheel-wander piezo sensors only needed a slot depth of one inch. Both slots were chipped out with relative ease with little refinement needed after the first inspection.

For access to the previously installed conduits, a four inch diameter core was cut at the end of the channels to a depth just below the elevation of the conduits. The conduits for the WIM slots were located just slightly deeper in the pavement than the wheel-wander strips. All of the conduits were located exactly under the layout marks.

Wheel Wander Sensors

The wheel-wander sensors consist of three PK piezo sensors manufactured by Electronique Controle Mesure of France (ECM) arranged in a “Z” or “N” grid on the pavement. Once the asphalt was removed from the channels for the wheel wander sensors, the void was cleaned thoroughly with compressed air and water. After this, the slots were dried completely with a propane brush burner and re-inspected to make absolutely sure the slots were dry. This is important because it allows the grout used to anchor the sensors have a good bond to the surrounding asphalt.

The sensors came with clips that held the sensor in the pavement slot at the proper elevation as shown in Figure 3-23. The clips were attached and the sensors were dry fitted into their appropriate slots. Once satisfactory, the sensors were removed and set aside. Tape was placed on the pavement along the edge of the slot. This would keep grout from getting onto the pavement and acted as an area for excess grout to be wiped off. The wheel-wander sensors were installed one at a time.

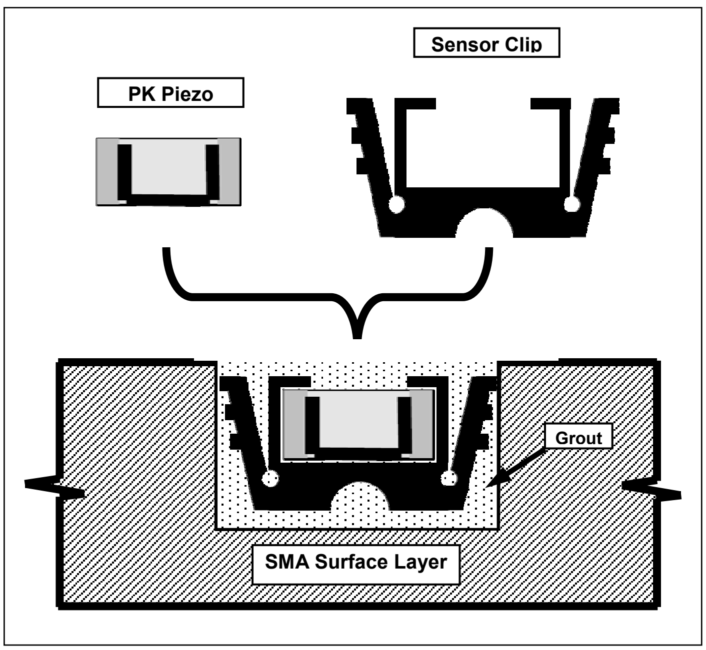

Figure 3-23 – Cross section of the PK piezo strip used for the wheel wander grid showing how it is assembled in the pavement.

One bag of grout was thoroughly mixed using a cordless drill and mixing paddle. The hardener was introduced and the grout was mixed again for three to five minutes. The slot was filled about half full with grout. The sensor was carefully lowered into grout being cautious that no voids would form between the sensor and grout. A supplied depth tool was used to further set the sensor to the proper depth within the slot. More grout was added as needed to fill the slot. Any excess grout was struck off with a trowel, finished flush with the surrounding pavement, and the grout was allowed to set and harden as shown on the left in Figure 3-24.

Figure 3-24 - Left: All three wheel-wander sensors have been installed and the grout on the final sensor is being leveled with the pavement surface before hardening. Right: All three sensors installed with the tape removed. Note the pictures have been taken from opposite sides.

While the grout was hardening, the other wheel-wander strips were installed using the same process. The grout on the sensors required constant attention during curing because the grout had the tendency to flow into any cavity, such as over-cuts, due to its rather low viscosity. After the grout had hardened (about fifteen to twenty minutes for the air temperature at the time of installation) the tape was removed and the pavement cleaned of any grout that may have spilled over. The finished sensors can be seen in the right photograph in Figure 3-24. According to the manufacturer, the sensors could be opened to traffic in about forty-five to sixty minutes leaving plenty of time for the length of the lane closure window. In the meantime the coaxial cables for the sensors were pulled into the conduits and into the lower pull-box. The coaxial cables were not quite long enough to reach into the cabinet and needed to be extended as well as have BNC style connector bodies installed.

The wheel-wander cable ended up being fifteen to twenty feet short of reaching into the cabinet. The BNC style connectors were crimped onto the wires located into the lower pull-box. Extension cables were made in the lab that were twenty feet long and each end of the cable received BNC connectors (it should be noted that the WIM and the wheel-wander sensors do not used the same style BNC connectors). The wheel-wander and extension cables were then connected using a coaxial “barrel” (essentially a double-ended male section that joins the two female connectors on the cables).

The connection was then coated in a layer of electrical tape followed by a paint-on seal coat and another layer of tape. The cables were then pulled into the cabinet and the spliced portion of the cable was pushed into the conduit adding extra protection from the environment.

Weigh-In-Motion Sensors

The WIM sensors consist of four Kister Quartz piezo WIM sensors which were pre-assembled in the lab beforehand. The pre-assembly consisted of mechanically joining two sensors end-to-end into one unit, turning four individual sensors into two units. All that was left to do in the field was to uncoil leads, make electrical property checks, tighten leveling bars, and install into the pavement. The electrical property checks included measurements of the sensors resistance and impedance and were measured using specialized tools on loan from the manufacturer. The identification, serial number, location, and orientation along with the measured electrical properties and temperature data were all documented in the Kistler Warranty Protocol. Copies of these documents were forwarded to the manufacturer as needed for the warranty.

After the channels had been chipped out, they needed to be cleaned and dried. The slots for the WIM quartz piezo sensors require extra care when preparing for installation. The pavement is required to be at a specified temperature before installation can begin in order to satisfy the warranty requirements set forth by the manufacturer. All of the channels were blown out with compressed air and dried with heat provided by a propane brush burner. A small amount of moisture was observed leaching out of the SMA layer, potentially causing a problem for installation of the sensors. It was reasoned that the recent wet weather and the porous nature of the SMA was to blame and the installation of the sensors was delayed until the following evening.

A special heating assembly was placed over the strips to initiate the heating process which is depicted in Figure 3-25. The heating assembly consisted of a series of HVAC ducting and a kerosene force air heater. Round sections of standard ducting from a home improvement store were bent to form a half circle and connected with other pieces of ducting that all came together at one junction. The forced air heater was then placed at this junction and blew hot air through ducting and over the slots in the pavement.


Figure 3-25 - The heating assembly was placed over the two slots cut for the WIM sensors. Heat was supplied by a forced-air kerosene fueled heater (not pictured). The sections of the assembly were sealed with aluminum ducting tape to minimize heat loss. Multiple temperature probes were in place to accurately measure pavement temperatures.

Three holes were drilled near the proximity of each sensor channel as dictated by the manufacturer's warranty protocol. Temperature probes were inserted into the holes and were monitored during initial heating and throughout the majority of the installation process. The hoods for the heaters were placed over the channels and the heat was turned on.

It would take almost three hours for the pavement to reach its required temperature of 68° F (20° C). Once the pavement had reached the required temperature for installation the temperature probes were removed and the data acquisition halted. The sensors were installed one at a time and the heating hoods where left running as long as possible and removed only to install and grind the sensors. The key was to get the pavement warm enough along with the ambient air temperature near the sensor to speed up the cure time of the grout. There is a recommended maximum temperature, but for the weather conditions during the operation, it was unlikely to ever exceed it as exhaust temperatures never rose above 100° F.

Once the heating hoods were moved out of the way, the sensors were dry-fitted into the channels. No adjustments to the channels were needed as the width of the channel was meticulously cut and the depth was the same as the pavement layer thickness, making for easy removal of material. Duct tape was placed around the perimeter of the channel to keep grout from getting on the pavement, thus making for easy cleanup and final grinding. At the end of the channel where the coaxial cable exited the sensor, pieces of foam were placed to prevent the grout spilling into the conduits. It was important to not have too much extra volume around the sensor itself because of the limited amount of grout available for each sensor.

When the sensor was dry fitted and half of the foam inserted into the end, the grout for the sensors was prepared. It is important that the grout be at a warm temperature due to its thick consistency, otherwise it can be difficult to mix. In this instance, the grout material, which is a mixture of a two-part epoxy and fine sand, was stored in a vehicle with the heat turned on. To mix the grout, the manufacturer recommends mixing the resin and sand first, blending well and then adding the hardener last. The pot life of the grout at room temperatures is only about fifteen minutes so it is important that the installations operations are done in a timely manner. To save time, the sand and resin can be pre-mixed several minutes before the introduction of the hardener component.

Once the hardener and resin had been combined, the grout was mixed for about five minutes or until well mixed. Half of the grout was poured into the channel and was spread around evenly using disposable plastic trowels depicted in Figure 3-26. Some of the grout was pushed up against the walls of the pavement channel making a “V” shape which helps the grout get around the sensor body and also works the grout into the pores of the asphalt surface. The sensor was then carefully lowered into the pavement until the leveling beams sat on the pavement surface. Immediately following, heavy pieces of steel were placed on the leveling beams to keep the sensors from floating out of the grout until it had cured. Plastic trowels were used to smooth out the surface of the grout left between the pavement and the top of the sensor. Because of the cohesive consistency of the grout getting a nice flat finish was difficult, especially after it began setting up. Some parts of the grout were left high and would be knocked down flat with the pavement during grinding.

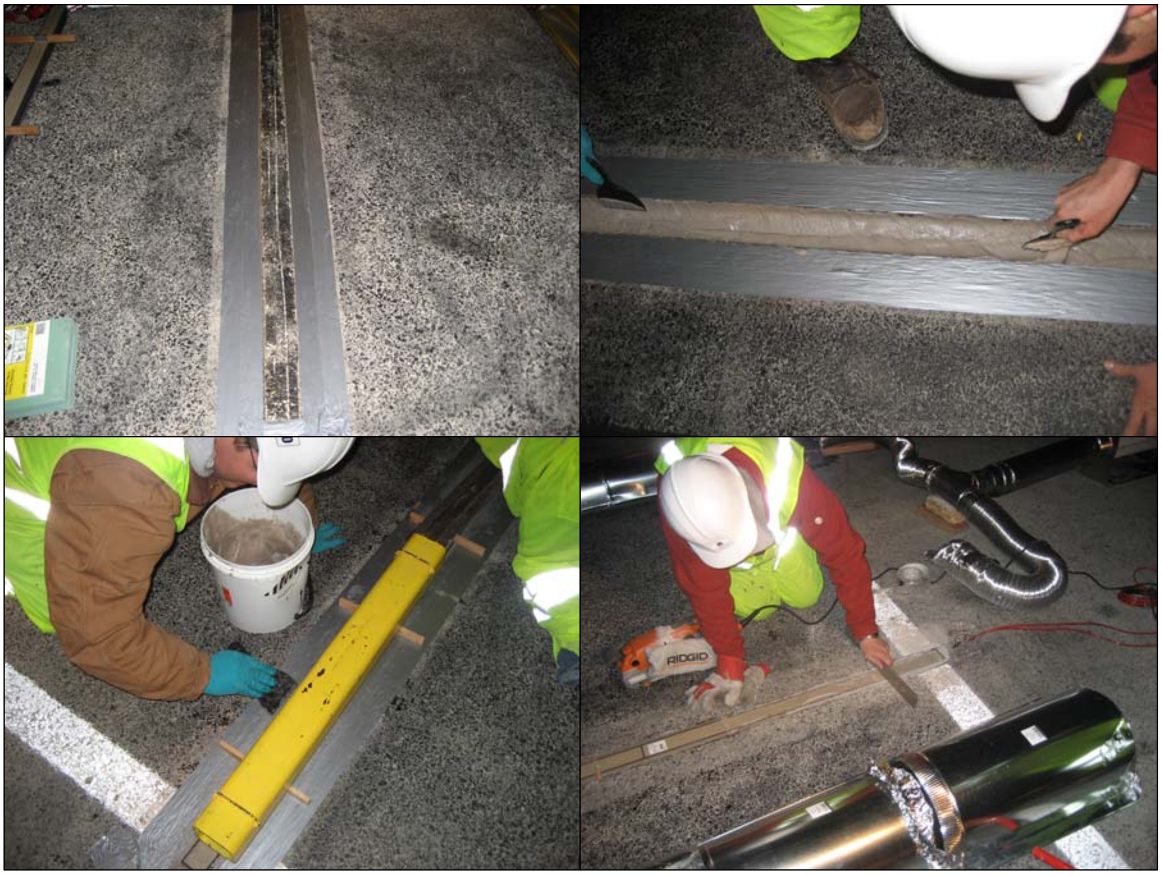

Figure 3-26 - Upper left: Channel for the WIM sensor ready for installation. Upper right: Grout for the sensor being distributed into the channel. Lower left: Sensor in place with pieces of steel placed across the leveling beams to keep sensor from floating out of the grout. Touch up work to the grout was done before its initial set. Lower right: The sensors were ground flush with the surrounding pavement and checked using an 18-inch long straight edge.

Once the first sensor was installed and curing, heat was reapplied. The second sensor was then prepared and the same process for installation was repeated. Total installation time from removal of heating hoods to the reapplication of heat was about one hour total for both sensors. Heating continued for both as long as possible to achieve the full strength of the grout. However, enough time had to be left to allow grinding the sensors flat, filling the conduits' voids with quick setting grout, and cleaning up. Heating continued for one-and-a-half hours at which point the grout should have been very near full strength based on a time-temperature maturity relationship provided by the manufacturer.

Grinding consisted of using a belt sander fitted with an alumina zirconia belt and an angle grinder with a general purpose grinding wheel to abrade away excess grout. The angle grinder was used for large amounts of grout needing removal, while the belt sander was used for the finish grinding. To check for flatness, an eighteen inch aluminum straight-edge was placed across the sensor (in the direction of traffic) at different locations. The pavement has to be perfectly smooth across the sensor or else they will not produce consistent measurements, thus degrading the accuracy of the WIM system.

During grinding, the ends of the sensor cable were protected and pulled through the conduits and up into the cabinet. The ends of the sensor cable were protected because it is very important that the sensor cable is not exposed to moisture or other contaminants that can cause signal loss. The sensor cables needed to have new BNC style connectors installed but this task was completed at a later time as the cut-off time for work was approaching.

Once the grinding had been completed, holes in the pavement exposing the conduits needed to be filled. Sealant was placed around the wire leads to prevent grout from entering the conduit and the foam placed at the ends of the sensors was also removed. Fast setting grout (leftover grout used for the wheel-wander sensors) was then poured into the holes up to the level of the pavement surface. Voids left in the pavement by over-cutting were also filled. Once the grout was nearing its full strength, the pavement was cleaned up and the highway was reopened to traffic. The finished products (including the wheel wander grid) are shown below in Figure 3-27.

Figure 3-27 – Test section opened to traffic with the wheel-wander and WIM sensors installed (circled areas).

The WIM sensor cables were long enough to reach into the cabinet but required new BNC connectors. The cables came with BNC connectors pre-installed, but it was not possible to pull the cables through the conduits with the connectors on so they had to be removed. The tools required to install the BNC connectors onto the WIM sensor cable were provided in the tool kit on loan from Kistler Instruments.

The charge amplifier for the WIM sensors was installed inside the cabinet using a plastic spacer block and bolted the chassis of the cabinet. Each WIM sensor strip is actually composed of two individual sensors with two separate leads, the cables "tee" into each other just before the charge amplifier. The plastic spacer block brings the charge amplifier away from the cabinet chassis so the cable connections can fit nicely with no interference and also making it easier to remove the cables if needed.

The WIM system is independent of the data acquisition system and data generated from the WIM system is exported to the database and is combined with the rest of the data. However the WIM system still functions like it would if it were a stand alone unit. Users can access the WIM controls and monitor vehicles as they pass over the system and modify the configuration settings. One very important step in setting up the WIM system is to calibrate the system using a test vehicle.

Setting up the WIM system is actually quite simple after the sensors are installed. Once the controller rack is placed into the cabinet a handful of sensor leads need to be connected. There are two wires for the loop detector that have two designated screw terminals and a BNC connection for the charge amplifier must be plugged in. The unit must also be plugged into an electrical receptacle for power. Beyond this, a connection to the controller must be made with a serial cable into a computer. Software provided with the equipment allows users to view data being generated by traffic and also change settings.

To calibrate the WIM a flat bed truck was used with a large weight placed in the back as shown in Figure 3-28. The total truck weights were obtained by driving the entire truck onto a static scale and recording the weight and then advancing the truck forward so that only the rear axle was measured. The scale platform was very flat, so this method should be accurate. To obtain individual wheel loads the axle weights were divided in two.

There are already plans to use portable scales provided by the Wisconsin State DOT to measure individual wheel loads. The truck used is owned by Marquette University and the large weight is easily loaded with a forklift. A standard positioning of the weight has been created so in the future, weighing out the wheel loads will not be necessary. Furthermore, when the wheel loads are measured, it is proposed to position the loaded truck so that it is on a similar cross-slope and grade as the test section to catch any weight bias between wheels.

Figure 3-28 - Vehicle used to calibrate the WIM system. Note the concrete slab placed in the bed of the truck over the rear axle.

To calibrate the system, the truck was driven over the WIM sensors while a user connected to the WIM system watched the response generated. To correct for speed adjustments the distance between the quartz piezo strips is modified in the software setup. If an accurate measurement of the spacing between the sensors has been made and entered into the software setup, it is unlikely that this will need to be modified.

To adjust the system for weight corrections, there is simply one correction factor that needs to be modified. There is actually a slider bar that can be clicked and changed, or the user can enter a factor by entering the number in the text box. These operations should only be done by a trained individual as there are many steps needed to get to these points. A detailed explanation is beyond the scope of this report.

3.2.9 Testing Procedures

This chapter highlights the tests and data collections conducted on various sensors and materials. The tests done on the sensors were done to confirm that the specific sensor had survived installation or not. In terms of materials testing, information was collected and archived for future research purposes.

Strain Data Collection During Paving

During the strain gauge installation, data was collected which included responses from the earth pressure cells as well as the strain gauges. Initially it appeared that one of the Dynatest gauges had not survived the installation (Dynatest C6). The data was downloaded and analyzed after paving. It should be noted that the heat generated from the asphalt material creates large fluctuations in the strain gauges due to the circuitry on board the gauges. Many of the signals had drifted out of the range of measurement, but did not necessarily mean the gauges were destroyed.

The following plots were generated from the rolling operations. Figure 3-29 and Figure 3-30 are examples of gauges that are functioning properly. They both show significant induced strain values, with two peaks indicating the time at which the steel wheel roller passed over the gauges. Figure 3-31 shows the output from the Dynatest C7 gauge which was showing a substantial amount of signal noise.

These plots confirmed that the gauges were functioning properly immediately after paving. More in-depth tests were carried out on the gauges the day following the paving and presented in the following section.

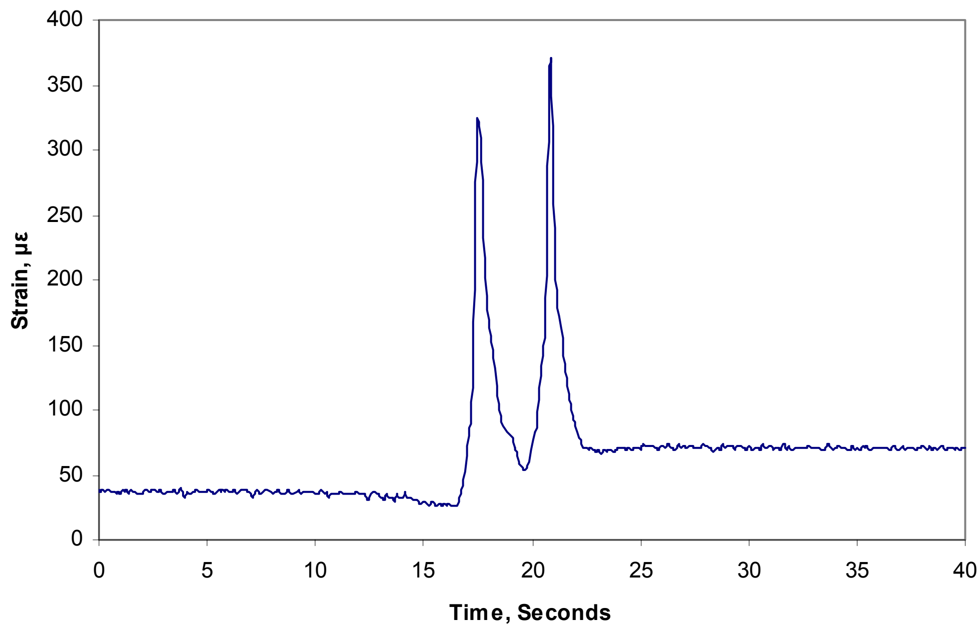

Figure 3-29 - Dynatest PAST II - AC gauge C4 response to roller pass.

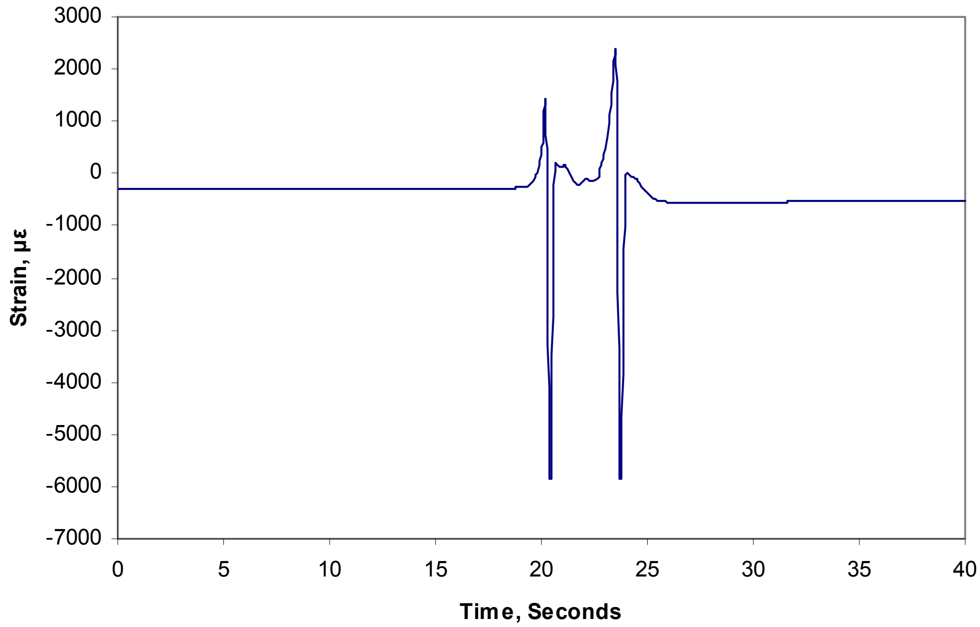

Figure 3-30 – CTL ASG gauge B0 response to roller pass.

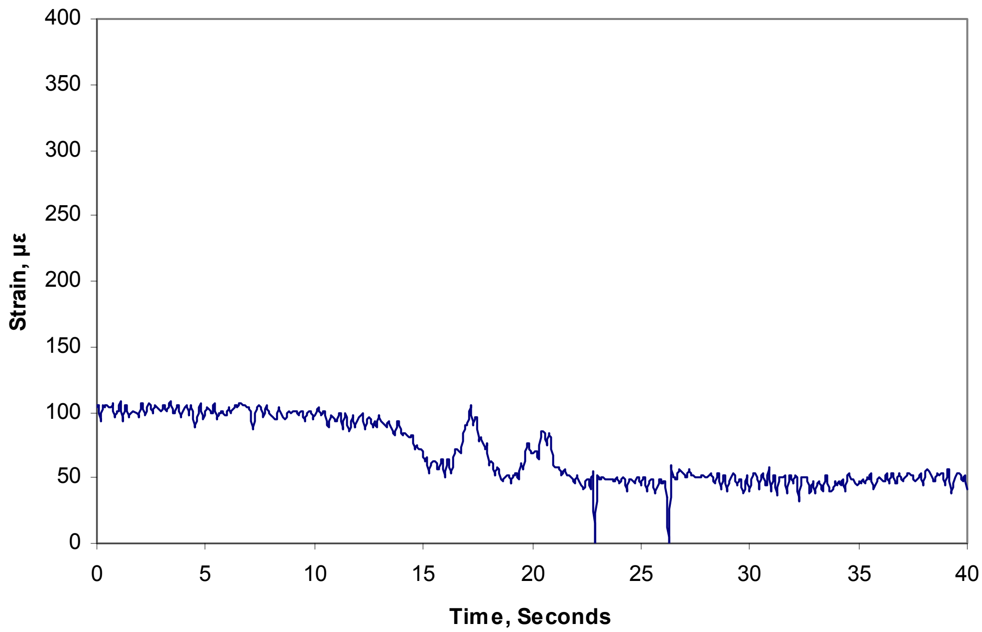

Figure 3-31 –Dynatest PAST II – AC gauge C7 output. Although not explicitly clear, this sensor has a substantial amount of signal noise compared to similar gauges.

Marshall Hammer Testing

This testing was conducted the day after the strain gauges were installed and was done so to check the functionality of the strain gauges. Each strain gauge was located using the GPS based location device and its position marked with paint directly on the pavement. The data acquisition systems were set up and all of the sensor leads connected. (Some sensors such as a few of the moisture and temperature probes were not measured or connected due to insufficient lead lengths that needed to be lengthened. Low speed samples were taken using a low speed data acquisition device set up for the purpose of measuring sensors during construction. The system purchased for the project was being set-up for taking high speed strain and pressure measurements.)

Once everything was connected and running, a series of tests were run to check that the sensors were alive and functioning. A Marshall hammer with a rubber pad on the foot was used to stimulate the ASG sensors with four drops in succession. The data acquisition system was started and stopped for each of the series of drops. The series of drops was conducted directly above each ASG sensors.

The data was downloaded and analyzed for functionality of the gauges. Upon inspection, one Dynatest strain gauge (Gauge ID - C6) was unresponsive to the Marshall Hammer drops. A subsequent resistance check of the gauge showed that the resistance was much higher than its gauge resistance of 120 ohms, indicating that the gauge (ID C6 in layout) was damaged and no longer functional (see Table 3-2 for the correct resistance values for the two types of strain gauges). Unfortunately, an adjacent strain gauge (DynaTest ID C7) appeared to have an unusual amount of signal noise. This was an indication that the gauge may have been damaged during paving. All of the CTL ASGs appeared to be in proper working order, as well as the earth pressure cells (although the pressure cells did not respond to the Marshall Hammer drops, passing vehicles did cause observed responses.)

Table 3-2 - Correct resistance values for the two different types of strain sensors. A resistance that is extremely high implies an open circuit. Resistance values lower than the correct value indicates that the sensor is shorting out.

Sensor	Sensor Lead 1	Sensor Lead 2	Correct Resistance Across Lead1 / Lead2, Ohms
CTL Asphalt Strain Gauge	Black	Red	350
	White	Green	350
Dynatest PAST II - AC	Black or Yellow	Blue or Brown	120

Figure 3-32 is a plot of the data generated from the tests using the Marshall Hammer on CTL gauge A0. The plot shows four significant increases in strain that seem to accumulate and slowly return to its previous state. The shape and behavior of these strain impulses were not of much interest at the time, but may be for future research. The point of conducting the test was to stimulate the sensors and get an indication of their functionality. Other gauges produced very similar results to this, with the exception of the damaged gauges.

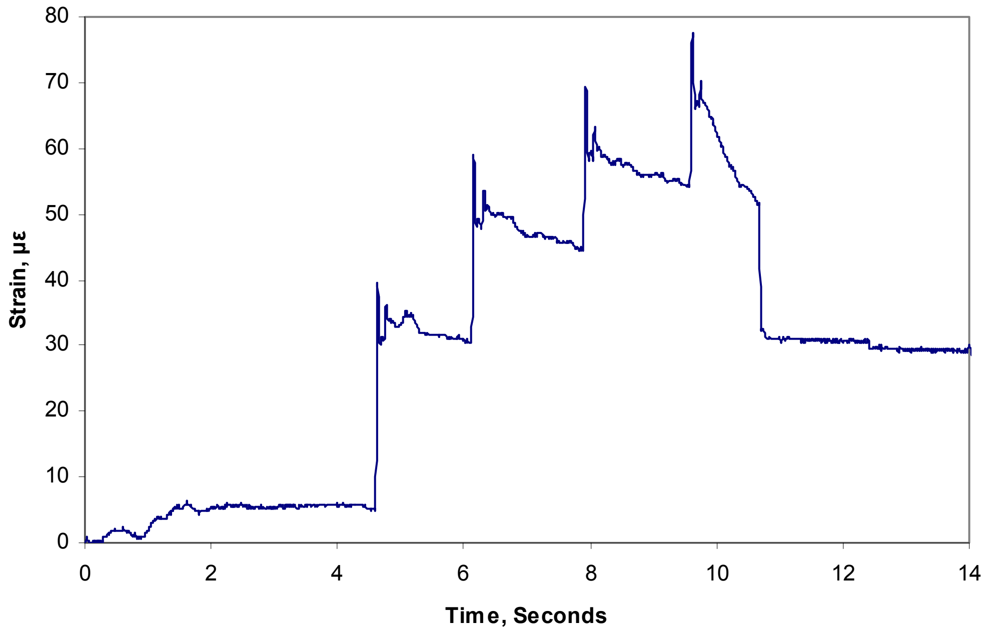

Figure 3-32 – CTL gauge A0 strain in response to a series of four Marshall Hammer drops in succession.

FWD Testing

The final lift of asphalt (SMA wearing surface) in the test section was scheduled for paving in the test section on the night of September seventh and finishing the next morning. Falling Weight Deflectometer (FWD) testing was done beforehand for two reasons. The first was to provide loading to the sensor arrays and record sensor data. The second reason was to record FWD data to gain some insight into the material properties of the pavement. Although FWD testing would be done after the pavement structure was complete, the data was collected as part of an effort to obtain as much information as possible about the pavement.

The FWD was used to create a heavy impulse loading on the pavement while simultaneously recording strain data. Although no detailed analyses of the data have been carried out as of right now, future research may find the data valuable.

FWD tests were done in a series of three tests, each with four drops. Figure 3-33 is a plot of strain response of gauge B1 due to the impulse loading of the FWD. Similar to the Marshall Hammer tests, we see the four distinct drops from the FWD and that the strains seem to accumulate with each drop. There is also a small recovery in between each drop, and over a longer period of time, there is almost a full recovery of strain to it pre-loaded state (this full recovery is not visible in Figure 3-33).

Another set of FWD tests was acquired on the completed pavement structure at a much later time. Since there was a very narrow window between the final SMA paving and the highway opening, FWD testing was not conducted during construction. However, a highway shutdown was used (night of October 25th into the following morning) to set a sign bridge structure and FWD testing was conducted on the finish pavement at that time.

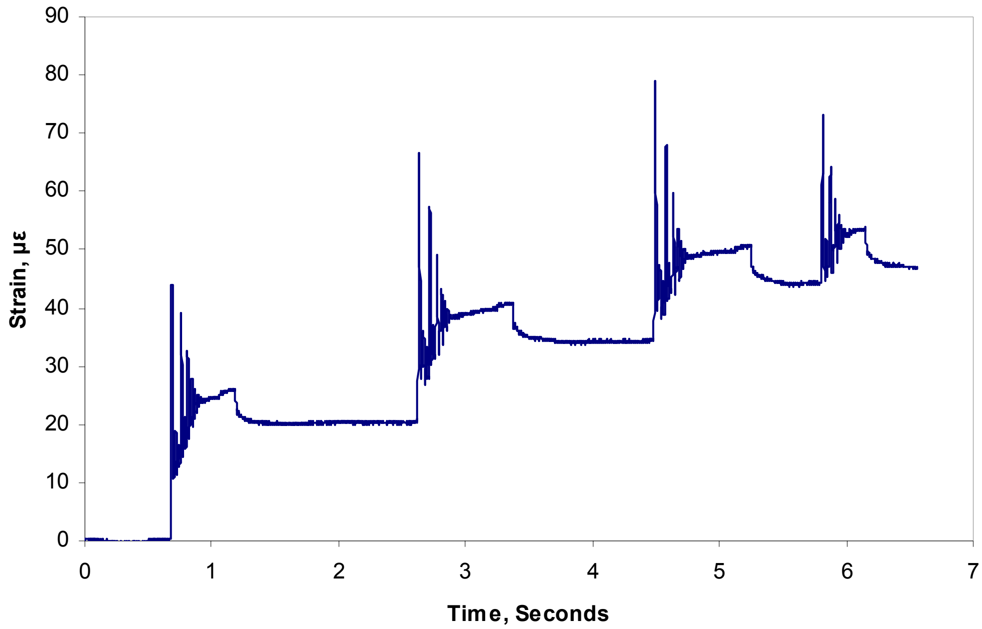

Figure 3-33 – CTL gauge B1 strain response to an impulse loads generated from and FWD.

3.2.10 Infrastructure

Some of the critical components of the project are merely incidental items, but took a considerable amount of time to install. These infrastructure components outline the basic framework and provide the necessary means to allow the system to exist. The designs used here were done so in the most simplistic and logical form.

Pull-boxes and Conduit Network

After the majority of the excavation of the Fond Du Lac (FDL) on-ramp concrete pads were cast which would be the future home of cabinets for both the ITS controllers and the equipment for this project. Along with these, pull-boxes were placed, along with conduits running between them. All of the electrical components were installed by Outdoor Lighting according to WisDOT specifications. Two pull-boxes were placed along side the mainline at stations corresponding to the center of the strain arrays and center of the weigh-in-motion/wheel wander systems. A third pull-box exists at an elevation below the roadside cabinet which serves as a drain for the entire conduit system. Open graded stone was used to backfill all of the pull-boxes to drain water. In the case of the pull-box located below the elevation of the cabinet, the backfill material extended, partially, into the select crushed layer and the dense and open graded base layers in the FDL on-ramp. This network is illustrated below in Figure 3-34.

A link between the two different cabinets does exist in the form of two two-inch conduits. One of the conduits is dedicated to supplying the project cabinet with power. Currently the other two-inch conduit is used being used by cables for the sensors mounted to the mast alongside the roadways (infrared thermometer and camera).

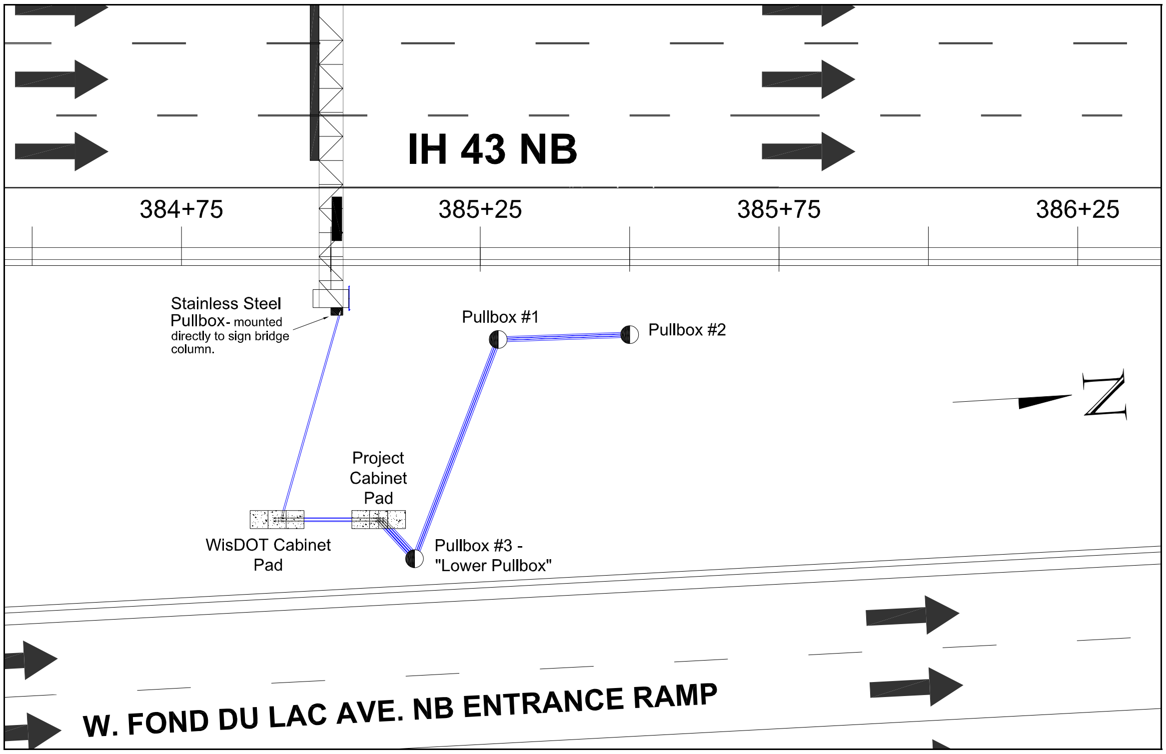

Figure 3-34 - Pullbox locations and the network of conduits connecting them.

Figure 3-34 above shows a conduit running from the column of the sign bridge running to the WisDOT ITS cabinet. The conduits at the sign bridge end are housed in a stainless-steel box. A weatherproof port and flexible conduit mounted into the side of the box allows access for the leads to the instrument mast.

Sensor Conduits - Part I

A week after the installation of the sub-grade sensor arrays and before slip-forming of the concrete curb, conduits were installed which would house wiring for the following equipment: strain gauge arrays, dense graded aggregate layer EPCs, temperature gradient probes, loop detector, wheel wander piezo strips, and weigh-in-motion quartz piezo strips. The layouts of these conduits are identified in Figure 3-35 within the clouded section.

At the time of installation of the conduits, the open graded base layer was being prepared for placement. In part of the test section it had already been placed and stockpiles of the material were left in various locations waiting to be cut to its finish grade. A large area was opened in the open graded aggregate layer along with some of the dense graded aggregate base layers to accommodate the installation of the numerous conduits. The conduits were installed into the lower layer of the dense graded base layer.

It was pre-determined to use a two inch diameter conduit for each strain sensor array and one inch diameter conduits for all others. The ends of the conduits for the earth pressure cells, strain arrays, and temperature gradient probes were placed so that they were as close as possible to the edge of the proposed sensor locations, minimizing the amount of exposed wires (this was difficult for the strain sensors, since eight sensors would use one conduit; adding cable armor to the leads took care of this). The ends of the conduits for the weigh-in-motion system, loop detector, and wheel wander strips, were terminated at the proposed face of the curb gutter and were later extended vertically to accommodate the higher elevations of the instruments. All of the placements of the conduits were made using the help of a GPS surveying locator tool.

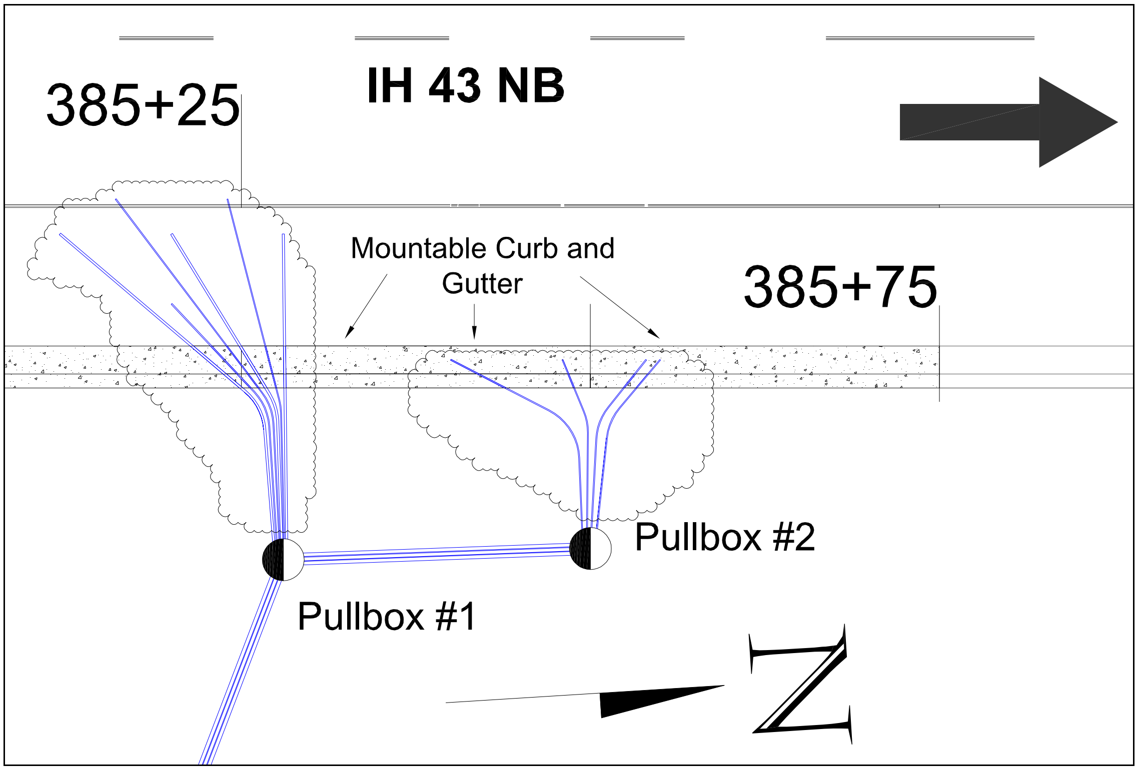

Figure 3-35 – The conduits within the cloud are those installed for the strain sensors, base EPCs, WIM and Wander components.

Since the proposed location of the weigh-in-motion system and wheel wander strips were farther north than the strain sensor arrays, the conduits were run to the northern pull-box which connects to the pull-box housing the strain arrays, pressure cells, etc. and finally into the lower pull-box and up into the cabinet.

After the proposed conduit termination locations were marked, the conduits were laid out, trimmed and inserted into the steel pull-box via ports cut with a hole-saw. The open ends of the conduits were covered with duct tape to prevent foreign material from entering. Before the conduits were backfilled, the exact locations of the ends of the conduits were measured and recorded so that they could be found later and are listed in Table 3-3. The dense graded base layer was replaced and compacted followed by the open graded base layer.

Care was taken to keep the layers separate, but some mixing of the layers was inevitable. The open graded base layer was re-worked and re-graded just prior to paving to remove any deficiencies.

Table 3-3 – Location of the conduit ends within the pavement structure. Conduits with an offset of 45.0 feet were terminated at the proposed curb face – in these cases, the locations below are not final and where later modified after paving.

Conduit Description	Conduit Diameter, in.	Station, ft	Offset (RT Of Mainline R/L), ft	Elevation, ft
Strain Array "A"	2	385+12	36.0	659.0
Strain Array "B"	2	385+20	36.0	659.0
Strain Array "C"	2	385+25	36.0	659.0
Base Earth Pressure Cell A1	1	385+16	33.5	659.0
Base Earth Pressure Cell B1	1	385+24	33.5	659.0
Shoulder Strain Gauge	1	385+20	41.0	659.0
Temperature Gradient Probes	1	385+20	45.0	659.6
Wheel Wander	1	385+36	45.0	659.6
WIM #1	1	385+48	45.0	659.6
WIM #2	1	385+54	45.0	659.6
WIM - Inductance Loop Detector	1	385+55	45.0	659.6

Sensor Conduits - Part II

At the time of installation of the base layer earth pressure cells the conduits for the WIM and wheel wander systems (WIM system includes the loop detector) needed to be extended appropriately. This was not done during the previous conduit work because the concrete mountable curb had not been slip-formed yet. After the curb was placed the conduits were located, excavated, and cut back accordingly to accept 90º elbows so the conduit would run vertically along the face of the flange. These would have to be repositioned once more after the upper layers of asphalt were placed.

Just before the SMA layer was scheduled to be paved, the conduits for the WIM sensors, wheel-wander sensors, and pavement temperature gradient probes were installed. The proposed locations for the sensors were marked on the pavement surface with paint. It was decided to use one one-inch diameter conduits for each WIM strip (two coaxial cables per conduit), one one-inch conduit for all three wheel-wander sensors (three coaxial cables per conduit) and one one-inch conduit to house both pavement temperature gradient sensors (two 16 conductor wires).

Most of the conduit runs for these components had already been complete prior to the placement of the concrete curb and were extended upwards against the face of the curb after it had been placed. Conduits needed to be installed into the pavement layer (the surface of the 7-inch E30 layer) that extended from the conduits at the curb to the edge of the proposed sensor location. Since the WIM and wheel-wander sensors needed to be installed into the surface of the SMA layer, it was proposed to install conduits so that only a small hole was needed to run the sensor cables to the cabinet, thus eliminating cutting unnecessary groves into the new pavement surface. However this was not needed for the pavement temperature sensors, as they would be installed during paving of the SMA layer.

For the two temperature sensors, grooves were cut from the stubbed up conduit at the curb line to the proposed sensor locations. The grooves were cut with a gas powered saw with an abrasive bladed mounted (Figure 3-36 - top left). The grooves were about ¾ inch wide and about ¾ inch deep, just large enough to accommodate the large diameter sensor leads that would be installed into it plus extra room for sealant to be used to secure the wire. One conduit would house both sensor leads. The holes for the temperature probes were not drilled until they were ready to be installed.

For the WIM and wheel-wander sensors, a much larger groove was needed to house the one-inch diameter conduits. A two-inch wide milling wheel mounted on a skid-loader was used to cut the pavement from the conduits to a location just short of the proposed sensor locations (Figure 3-36 - top right). The pavement around the conduits had been cut open and exposed by hand, making it possible to install elbows onto the previously installed conduit stubs.

After the grooves for the WIM sensors were cut, the conduits were placed in the groove. The conduit for the wheel-wander had three extra cuts made that would accommodate the three sensor leads. Pieces of armor cable were used to create smaller access channels for the sensor leads that extended from the base of the proposed wheel-wander sensor locations and inserted into the conduit (though this made it possible to push the wires in only one direction). It is important to note that sharp edges exist on the armor cable when freshly cut and were covered with electrical tape to prevent damage to the sensor leads. In the future it is advised to use flexible tubing that has a smooth interior wall as pushing wire through the armor cable proved to be quite difficult. It is also important that all conduits are sealed tightly just prior to being buried or debris, especially fine material, can be carried into the conduits creating blockages.

Figure 3-36 - Installation of the WIM, wheel wander, and temperature sensor conduits. Top left: Grooves were cut with a saw for the sensor leads for the pavement temperature gradient probes. Top right and bottom left: Groove cut with conduit in place for a WIM sensor. Bottom right: Asphalt being re-compacted into groove cut for the wheel-wander sensors. The plate tamper had a bolt-on bar (circled) mounted on the bottom to fit into the cut to increase compaction efficiency.

After all of the conduits were placed in their proper locations, the exact location of the ends the conduits were measured with the GPS locator and also by using a set of triangulation points. The triangulation points were based off of three nails that were installed into the concrete curb, all of which were located near saw-cut construction joints towards the back of the curb.

Fresh asphalt was then replaced into the grooves in the pavement as seen in the bottom photographs in Figure 3-36 above. Some areas were compacted by hand using a hand tamper, while most the longitudinal portions of the groove were compacted with a gas powered plate-tamper. The day after the conduits were placed, the bucket of a skid-loader was used to trim the re-compacted asphalt flat with the surrounding pavement.

3.2.11 Miscellaneous Project Activities

A handful of other tasks were carried out that were important but were not involved with the installation of any equipment. Some of these tasks were important because they dealt with gathering information for future research while others were just observations, but considered noteworthy.

Site Survey and Soil Sampling

As most typical construction projects go, progress takes place in multiple stages. The first steps taken in accomplishing the goal of this project were to take a couple of site surveys where general information was gathered about the chosen location. The initial visits were made before any demolition of the existing pavement and occurred in late April. The first task in the project which consisted of collecting soil samples didn't take place until mid-June.

The project detailed a change in the design of the Fond du Lac (FDL) on-ramp, adjacent to the test section. The existing ramp had a pavement elevation slightly higher than the mainline elevation. The proposed ramp would be many feet below the previous design, thus calling for major work in constructing a secant-pile retaining wall and removal of large amount of soil. Excavation of the ramp at the test location would have to wait until the retaining wall was complete so that excavation of the entire section could begin.

As soon as the mainline excavation was finishing up, select crushed material was placed and graded. Shortly thereafter, excavation began for a sign bridge structure, which included a series of piles for the foundation (it was noted that a large deposit of very gravelly material existed in the excavation for the piles, most likely due some pre-existing construction. It was also noticed that the soil was very wet and the excavation for the piles had to be constantly pumped out. Soils in the excavation were mostly clays). As the structure was being constructed samples of the sub-grade soils were taken at the proposed mainline elevations of the sub-grade (or native materials) from earth slope between the mainline and the FDL on ramp as shown in Figure 3-37.

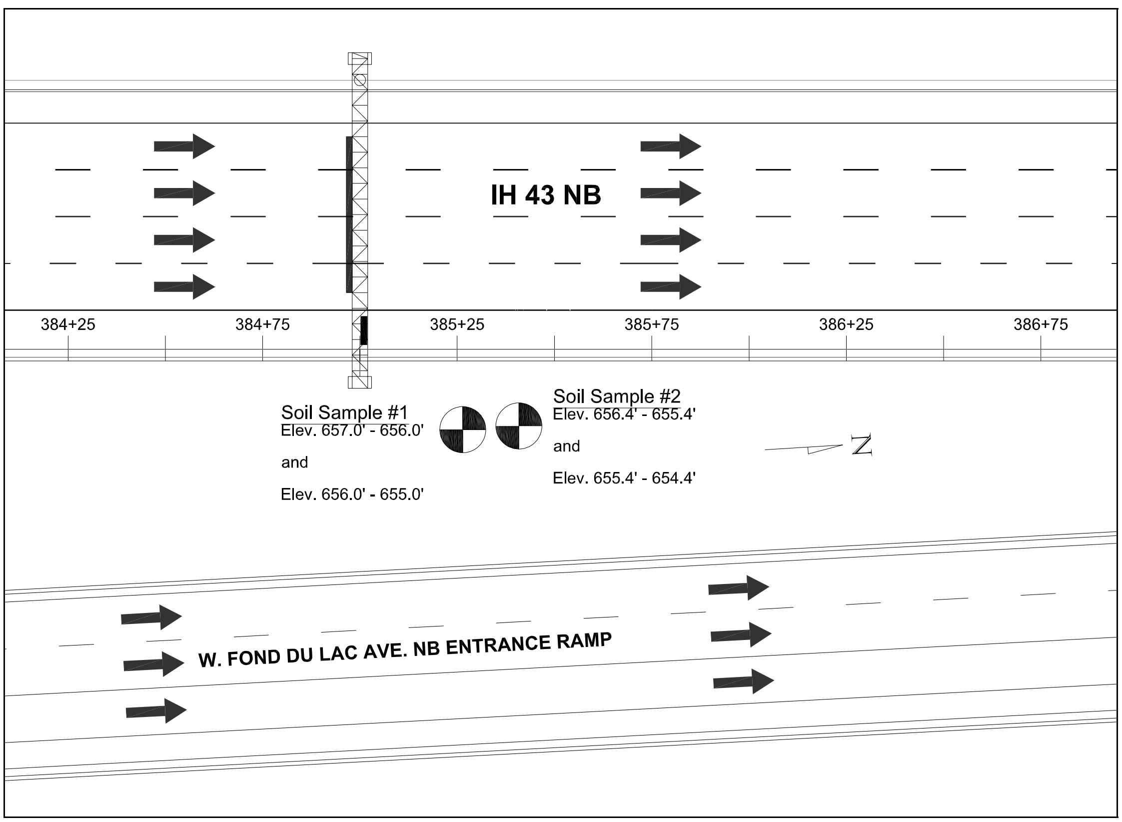

Figure 3-37 - Location of soil samples taken for the project.

The types of soils taken from these locations varied significantly in the small amount of distance that separated them. The soils taken from location #1 in Figure 3-37 were generally very clayey with some gravel throughout. The samples from the location #2 in Figure 3-37 could be better characterized as silty-clays. It was somewhat unknown what the states of the materials were in regards to the previous construction of the highway many years ago. During construction it was noticed that several locations had seams of very gravelly material which, upon further inspection, appeared to be locations of an old system of sewers or other ducts. When installation took place, the soils in the location of the test section appeared to be in an undisturbed state and are assumed to be such.

Pavement Coring

Permission was granted from the guarantor of the pavement to take four four-inch-diameter cores samples, just prior to final of the SMA layer, for future testing and other uses (see Figure 3-38 below). They were taken a substantial distance away from the test section; two taken south of the test section and another two north of the section. Upon removal of one core, the upper pavement layer (upper lift of E30 mix, the SMA layer had yet to be paved) fell away from the rest of the layers. The bond between layers has not been investigated, so the only action taken was to take note of the observation. The core samples were taken back to the lab at Marquette University, preserved by packaging them appropriately, and are currently in storage.

The voids left by the coring were re-compacted in the proper lifts using the properly matched material. A Marshall Hammer was used to compact the asphalt and were finished as flush as possible to the pavement adjacent to it.

Figure 3-38 – Left: Core sample removed from the pavement. Right: The core-drill was secured against the weight of a vehicle to produce samples with very smooth side walls for possible future testing.

Sign Bridge Lift

Poor weather conditions had pushed some of final construction activities behind schedule. It was due to these delays that the wheel-wander and WIM sensors were installed using nightly lane closures, whereas the original plans called for installing them before the highway opened. One aspect of construction that was pushed behind schedule was the erection of large sign bridge structure near station 385+00, just south of the test section.

The sign bridge structure was supposed to be erected before SMA paving, but unknown issues prevented it from being installed. Lagging was set up along roadside in the areas of the project pull-boxes, and the sign structure was lifted and placed on it. The structure remained there until after SMA paving and barrier walls were erected just before the highway opening.

Installation of the sign bridge was scheduled for October 25th and 26th during a night-time full highway closure. The entire highway had to be closed because a heavy crane was brought in to lift the sign structure as one unit over all lanes of traffic as shown in Figure 3-39. The physical positioning of the crane and its outriggers on the pavement was unknown, but it was understood that this could potentially damage the surface mounted instruments. The operation was monitored throughout equipment set-up and lifting. The crews were notified of the sensitive pavement and were very cooperative with avoiding the area.

The closure time was also used as a window to conduct FWD testing on the finished pavement structure. The testing was done in multiple locations while the construction crews were awaiting the arrival of their equipment.

Figure 3-39 - Heavy crane lowering the sign bridge into its final resting position. Note that the outriggers for the crane came close to the sensor locations.

Chapter 4 - System Demonstration

The final step of the first phase of this project was a demonstration of the system verifying to WisDOT the functionality of the system. This specific step fulfils task 4 of the original research proposal. This step proved, to the appropriate WisDOT personnel, the ability of the system to successfully record data from the test section and properly store it on the database at Marquette University. The format of the data base tables and the tools to access them are also presented here.

4.1 System Demonstration

On April 18th, the system was demonstrated to selected WisDOT personnel. The data viewer was used to show the data being measured in real time and a MySQL query was used to find the data associated with the data being recorded and stored. The strain and pressure profile, wheel, environmental, and WIM tables were all accessed to show the data being stored to the server. The WisDOT personnel agreed to recommend acceptance of the system.

4.2 Database

There are a handful of different database types available for use on the market today, each with its own unique capabilities depending on the product's intended use. For this project the database was built with the open source MySQL software. This particular software is equivalent and compatible with Microsoft's SQL server, however because it is open source, the software and the required tools to access the database are all provided for free. For users needing to access data within the database the MySQL Query Browser is an excellent tool for doing this. The MySQL software can be downloaded directly from their website: http://www.mysql.com. Database software such as Microsoft Access is simply not robust enough for the amount of data being stored and the access requirements for this project.

Structured Query Language, or commonly known as simply SQL, is a standardized language used to create, modify, retrieve, and delete entries in a relational database. SQL has been standardized by both the American National Standards Institute (ANSI) and International Organization for Standardization (ISO). The programming language and syntax is outside the scope of this report, however most individuals comfortable with programming should be familiar with SQL and database theories. Furthermore, most programming languages such as C#, C++, Java, and many others provide very easy tools for accessing and manipulating databases.

The database is being populated directly from the National Instruments data acquisition system in the field via the wireless connection. Data from the WIM system is exported to the National Instruments system and sent with the other data streams. The wireless connection drops into Marquette's local network through a hardwired data link in Carpenter Tower Hall located on the corner of 11th and Wisconsin Avenue. Once within the local network the data has direct capabilities to the database computer. A pictorial representation is shown below.

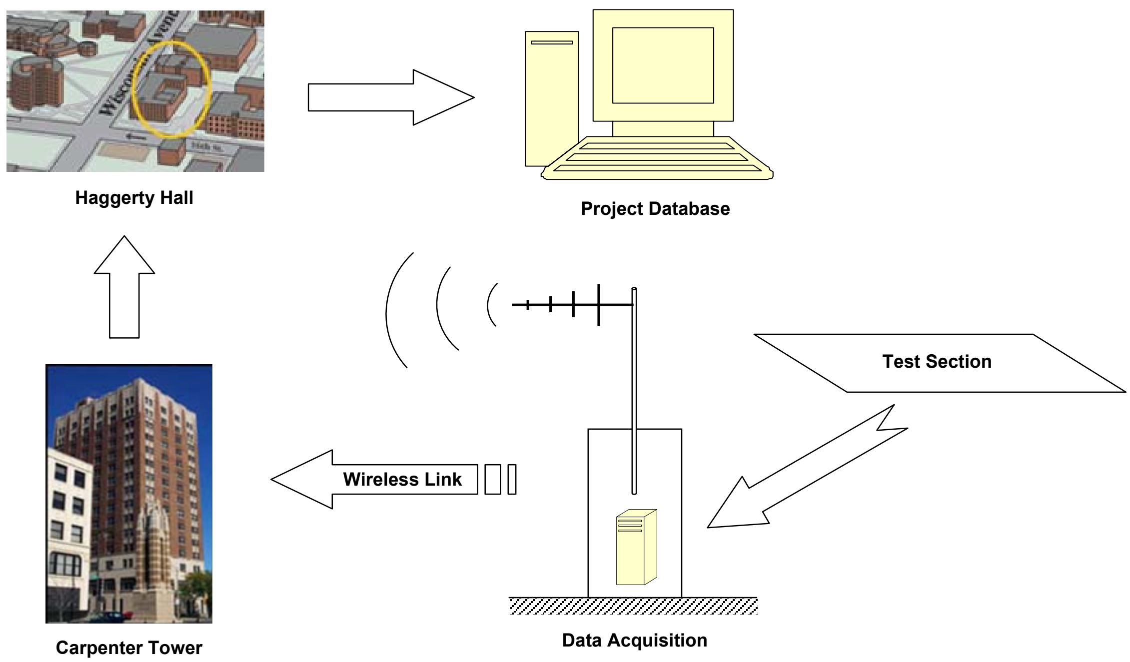

Figure 4-1 – Data transmission path.

The WIM data and the data recorded from the data acquisition system are not tied together at any point. The two systems operate independently and store data independently in separate tables. However, the tables can be joined by time stamps applied to each row of data. The time stamps are not perfectly synchronized, but are within a narrow margin of each other. This does not limit the ability to match data rows; a simple fix can be accomplished by creating a query that takes this margin into account.

Data being measured from the data acquisition system is stored in separate tables along with the WIM data. The break down of the tables and their contents are shown below. There is a primary key for the wheel table only. The environmental table contains data which is rather low speed data and is organized by date and time stamps. The profile table contains the high speed data from the strain sensors and the earth pressure cells. This table does not posses a primary key because one unique wheel identification number belongs to many rows of strain and pressure data; hence a one-to-many relationship between the two. Again, because the WIM is an independent system, the WIM table is related to the profile and wheel table via date and time stamps.

	Profile
	wheel_id strain_A0 strain_A1 strain_A2 strain_A3 strain_A4 strain_A5 strain_A6 strain_A7 strain_B0 strain_B1 strain_B2 strain_B3 strain_B4 strain_B5 strain_B6 strain_B7 strain_C0 strain_C1 strain_C2 strain_C3 strain_C4 strain_C5 strain_C6 strain_C7 strain_S0 subgrade_pressure_A0 base_pressure_A1 subgrade_pressure_B0 base_pressure_B1

	WIM
	date time ms axle class weight length speed vehicle_number axle_sp_1_2 axle_sp_2_3 axle_sp_3_4 axle_sp_4_5 axle_sp_5_6 axle_sp_6_7 axle_sp_7_8 axle_sp_8_9 wheel_load_1 wheel_load_2 wheel_load_3 wheel_load_4 wheel_load_5 wheel_load_6 wheel_load_7 wheel_load_8

	Environment
	date time air_temperature wind_speed pyro_0 pyro_1 pavement_surface_temperature subgrade_moisture_A0 subgrade_moisture_A1 subgrade_moisture_A2 subgrade_moisture_B0 subgrade_moisture_B1 subgrade_moisture_B2 subgrade_temperature_A0 subgrade_temperature_A1 subgrade_temperature_A2 subgrade_temperature_B0 subgrade_temperature_B1 subgrade_temperature_B2 pavement_temperature_A0 pavement_temperature_A2 pavement_temperature_A3 pavement_temperature_A4 pavement_temperature_A5 pavement_temperature_A6 pavement_temperature_A7 pavement_temperature_A8 pavement_temperature_A9 pavement_temperature_A10 pavement_temperature_A11

	Wheel
PK	**wheel_id**
	date time ms offset speed image

Figure 4-2 - Database tables.

4.3 Data Viewer

A data viewer tool has been developed so that a user can literally “watch” the system at work. This tool gives the user a view of the system real time. It is possible for a user to watch data entering the database, however at peak traffic times, it is likely that a queue may develop which consist of data at the field site waiting to be sent to the database. This is mainly due to the data transfer rate limitation of the wireless communication system. At off-peak traffic hours though, the queue will diminish and be at real time.

The data viewer allows the user to see the system real time. It provides the user with all of the data being taken at the very instant it is recorded. This includes strains, pressures, environmental data, WIM data, and provides a still image of the vehicle. Below is a screen-shot showing the viewer. The viewer was something added on after the fact and will certainly undergo minor adjustments and changes as improvements are seen fit. This interface will likely only be available to those managing the system, as there is significant consumption of the wireless communication bandwidth and network security issues.

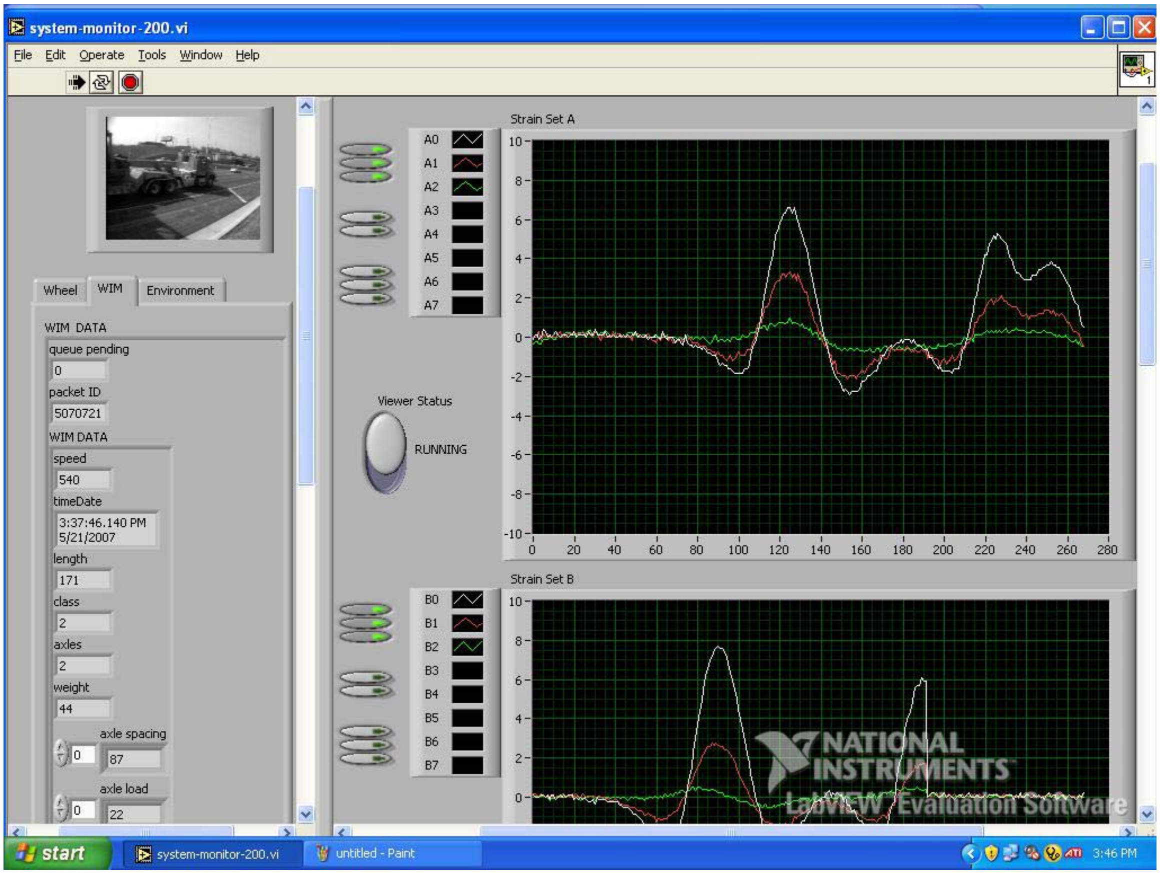

Figure 4-3 - Screenshot of data viewer

In the left panel of the display the user can see a picture of the current vehicle in a black and white still image. Just below this there are three tabs; wheel, WIM, and environment. Within each tab, data associated with each is displayed directly below. The wheel tab contains general information regarding the status of the system and the current wheel load. The WIM tab displays information regarding current axle such as wheel weight, spacing, etc. using information from the WIM system. Environmental data such as temperatures and wind speed are displayed in the environment tab.

The right panel of the screen shows the data from the strain and pressure recordation from the current wheel load. There are four plots aligned vertically within this window, one for each strain array and the fourth for earth pressure.

Buttons to the left of each plot are available to either turn on or off the trace for each individual sensor (the screen shot below was taken before this feature was added); as many of all of the sensors or as little as none can be displayed.

A similar version of this tool will be developed for the general public. The difference will be that this version will be showing the user the latest data entering the database. This isolates the data acquisition and transfer processes from the data access processes caused by outside users. Thus a technical breakdown in this change of information does not affect the data being measured and stored.

4.4 Phase II Work Plan

This Phase II work plan was developed to provide a continuation of data collection, storage and download as well as to develop automated data analysis techniques for accumulated strain data. Additionally, accumulated wheel wander and weigh-in-motion data will be analyzed to validate and/or refine general models used within the mechanistic-empirical (ME) pavement design procedures.

The array of pavement sensors installed for this project, coupled with their associated sampling rates, will yield a large volume of data that must be effectively managed if any discernable results are to be obtained. While the system has the capability of capturing the response of individual axle loadings, it may not be desirable to record this data for every single axle loading using the facility. In contrast, repeated short data collection windows may be desired to gather axle loadings and related responses at selected times and then grouped to provide a more comprehensive overview of the aggregate pavement performance. The key indicator in the choice of operating environments will be the processing time required to effectively and accurately analyze collected data.

The following work tasks summarize the activities proposed for Phase II of this research project. The initial findings from study Phase I have been integrated into this Phase 2 work plan to provide maximum benefit for this research effort.

Task 1 – Maintain System Integrity

All installed pavement sensors and data recording/transfer hardware will be monitored to ensure the integrity of the data collection system is maintained throughout the Phase II work period. Any external sensors, including the pyranometers, anemometer, infrared pavement temperature sensor and video camera will be repaired/replaced as needed. The National Instrument and weigh-in-motion data collection system systems will be monitored and repaired as needed. Replacement of these systems, if necessary, will be covered by manufacturer's warranties or WisDOT as appropriate. The roadside and roof-mounted wireless access systems will be maintained as necessary to provide continued data transmission.

Task 2 – Develop Data Packages

The large amounts for pavement data being generated on this project will necessitate the development of protocol for efficiently storing field data sets. Additionally, a website for downloading data sets will be developed to provide researchers around the globe with access to collected data. Posting of collected data will continue throughout the duration of Phase II work activities.

Task 3- Develop Automated Data Processing Techniques

The installed pavement instrumentation has the capability of collecting and storing substantial quantities of pavement strain data for each axle load passage. This strain data represents a critical link between traffic loads and accumulated fatigue damage. The efficient analysis of strain response requires the development of automated data processing algorithms to produce meaningful summary values for ME pavement analysis. Data processing algorithms for the wander and weigh-in-motion data will also be developed to validate/refine general models used in ME design.

Task 4 – Project Reports

The project tem will prepare five quarterly progress reports which will provide WHRP and WisDOT an opportunity to review recent project accomplishments. A Phase II Final Report will be submitted which documents all findings of this study phase and provides a procedural manual for the visualization/recordation/analysis of pavement response data. A draft final report will be submitted for review by March 31, 2008. A revised final report, incorporating reviewer comments as appropriate, will be submitted by June 30, 2008. The final report will also include recommendations for implementing the study findings into WisDOT pavement design policies.

Phase II Timeline

A Phase II period extending through the end of June, 2008 is needed to allow for a complete year of field data collection and analysis and report preparation/review. Works Tasks 1 & 2 will be continuous throughout Phase II. Work Task 3 will be completed by December 2007. A Draft Final Phase II report will be submitted by March 31, 2008. A 2-month review period will be provided for comments by WisDOT personnel and Flexible Pavement TOC members. Review comments will be incorporated into the Phase II Final Report which will be submitted by June 30, 2008.

Table 4-1 - Phase II work schedule.

Phase II Project Task	CY 2007							CY 2008					
	J	J	A	S	O	N	D	J	F	M	A	M	J
Task 1:Maintain System Integrity													
Task 2: Develop Data Packages													
Task 3: Develop Automated Data Analysis Techniques													
Task : Report Preparation											R	R	

Table 4-2 - Phase II budget estimate.

Individuals	Task1	Task2	Task3	Task4	FFY2007	FFY2008	TOTALS
JA Crovetti - PI	2,694	2,155	2,155	2,155	3,663	5,495	9,158
JP Schabelski	2,592	2,592	2,592	2,592	4,147	6,221	10,368
Research Assistant	4,320	5,184	6,048	5,184	8,294	12,442	20,736
Direct Labor	9,606	9,931	10,795	9,931	16,105	24,157	40,262
Other Direct Expenses	2,250	500	300	800	1,540	2,310	3,850
Total Direct	11,856	10,431	11,095	10,731	17,645	26,467	44,112
Indirect	5,572	4,903	5,215	5,044	8,293	12,440	20,733
Total	17,428	15,333	16,309	15,774	25,938	38,907	64,845

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Appendix A – Strain Gauge Calibration Data

Table A-1 – CTL strain sensor calibration factors.

Gauge ID	Provided Sensitivity Factor, με/mV	V Ex., V	Provided Cal. Corrected	Experimental Sensitivity Factor, με/V@ 5V	y-intercept, με	Strain Card Identification
I67	109.3	5.116	111.8	126390	-639.8	A0
I68	114.1	5.116	116.7	127220	-110.0	A1
I69	108.5	5.213	113.1	122830	-2192.8	A2
I70	119.7	5.213	124.8	137580	-87.3	A3
I71	107.8	5.213	112.4	131050	1852.7	A4
I72	106.5	5.213	111.0	121990	1400.5	A5
I73	104.7	5.331	111.6	135290	1314.8	A6
I74	105.6	5.331	112.6	120180	952.5	A7
I75	101.9	5.331	108.6	118880	1787.6	B0
I76	103.4	5.331	110.2	107850	2459.3	B1
I77	113.3	5.134	116.3	110700	425.0	B2
I78	111.4	5.134	114.4	103830	747.6	B3
I79	113.8	5.134	116.8	119250	720.7	B4
I80	120.6	5.134	123.8	132190	1222.5	B5
I81	99.0	5.146	101.9	120330	1088.2	B6
I82	112.4	5.146	115.7	120490	841.0	B7
I110	111.5	5.120	114.2	136230	-131.1	D5 - Shoulder

Table A-2 - Dynatest strain sensor calibration factors.

Gauge ID	Bridge Output Sensitivity, με/mV	Experimental Sensitivity, με/mV		Final Sensitivity		Strain Card Identification
		Side One	Side Two	Slope, με/V	y-intercept, με	
679-001	800.0	700.3	780.6	-780650.0	-9751.7	C0
679-002	800.0	788.0	754.1	-785690.0	-9655.5	C1
679-003	800.0	717.9	758.7	-758440.0	-11599.2	C2
679-004	800.0	811.0	744.6	-810120.0	-13539.1	C3
679-005	800.0	869.6	801.3	-800880.0	-10649.7	C4
679-006	800.0	716.8	804.5	-802060.0	-10171.4	C5
679-007	800.0	775.2	724.1	-774760.0	-11680.4	C6
679-008	800.0	670.2	808.4	-807910.0	-11506.9	C7

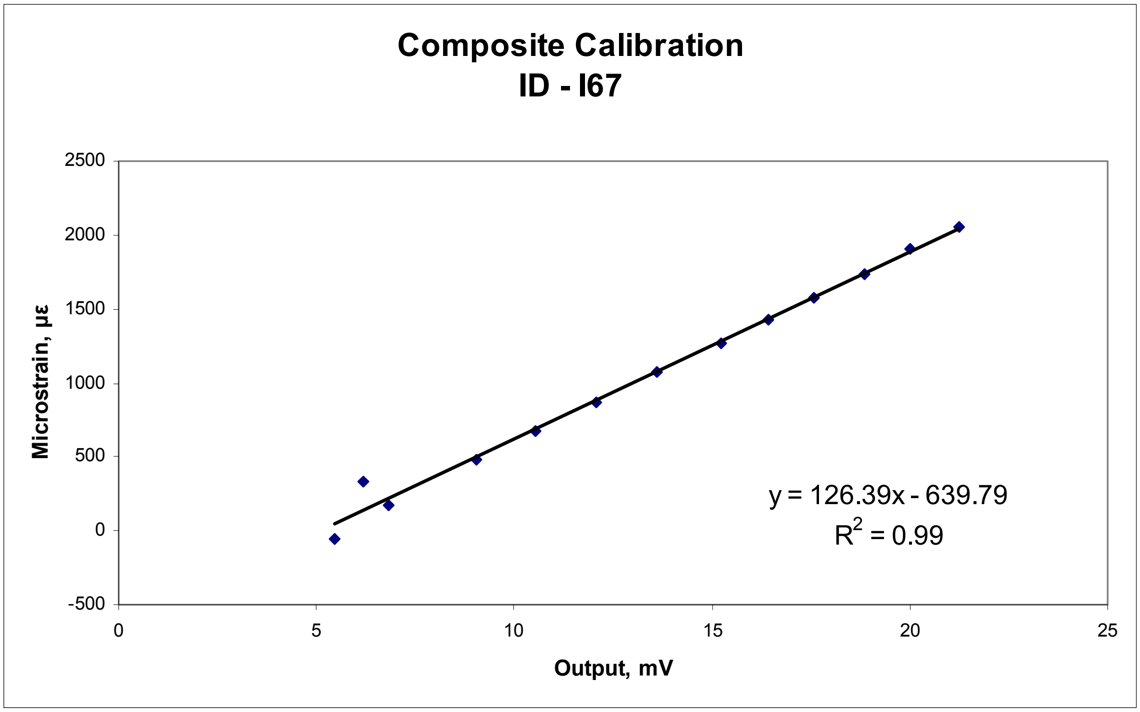


Figure A-1 - CTL gauge I67/A0

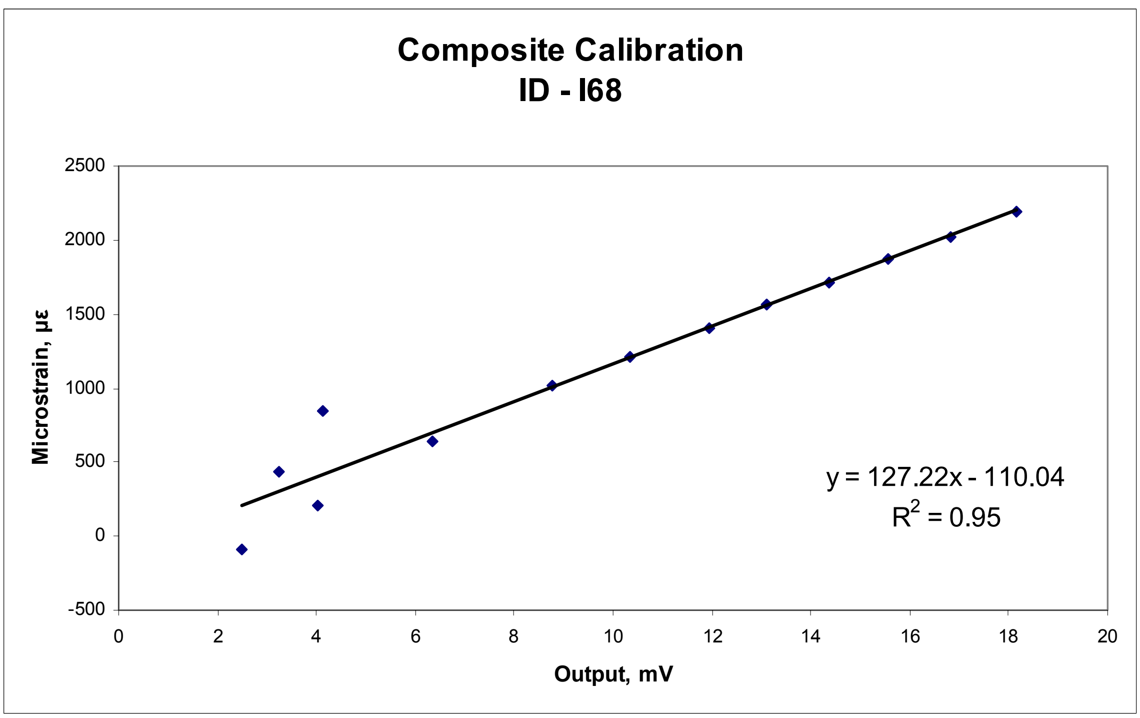


Figure A-2 - CTL gauge I68/A1

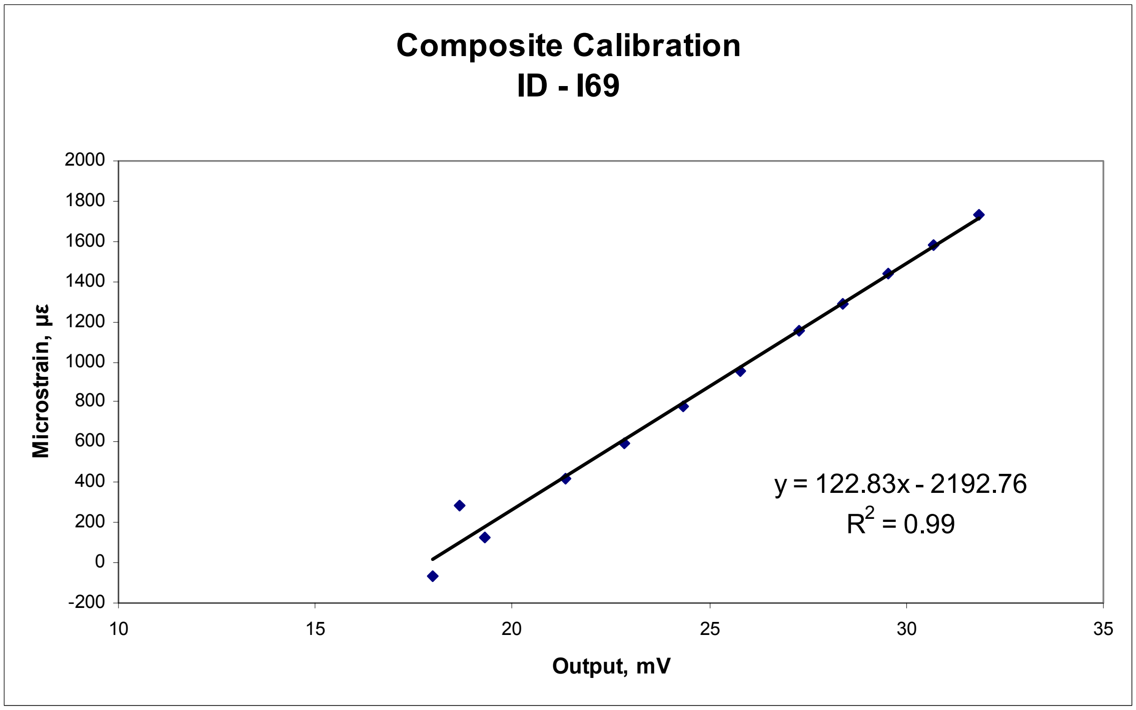


Figure A-3 - CTL gauge I69/A2

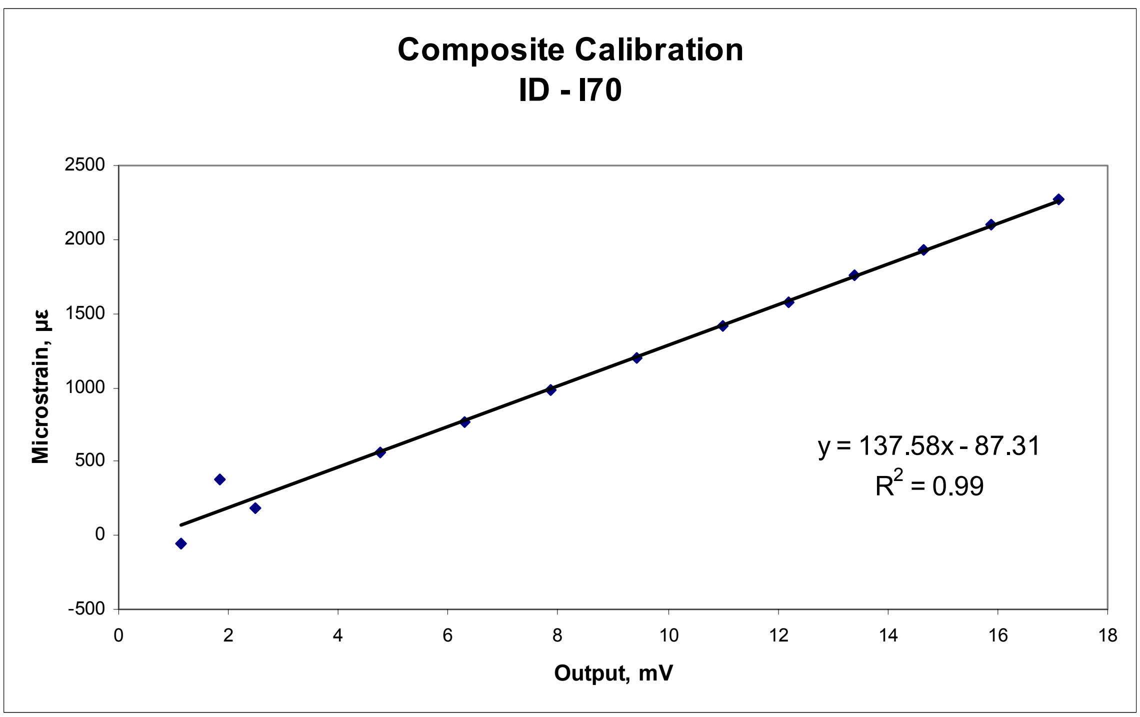


Figure A-4 - CTL gauge I70/A3

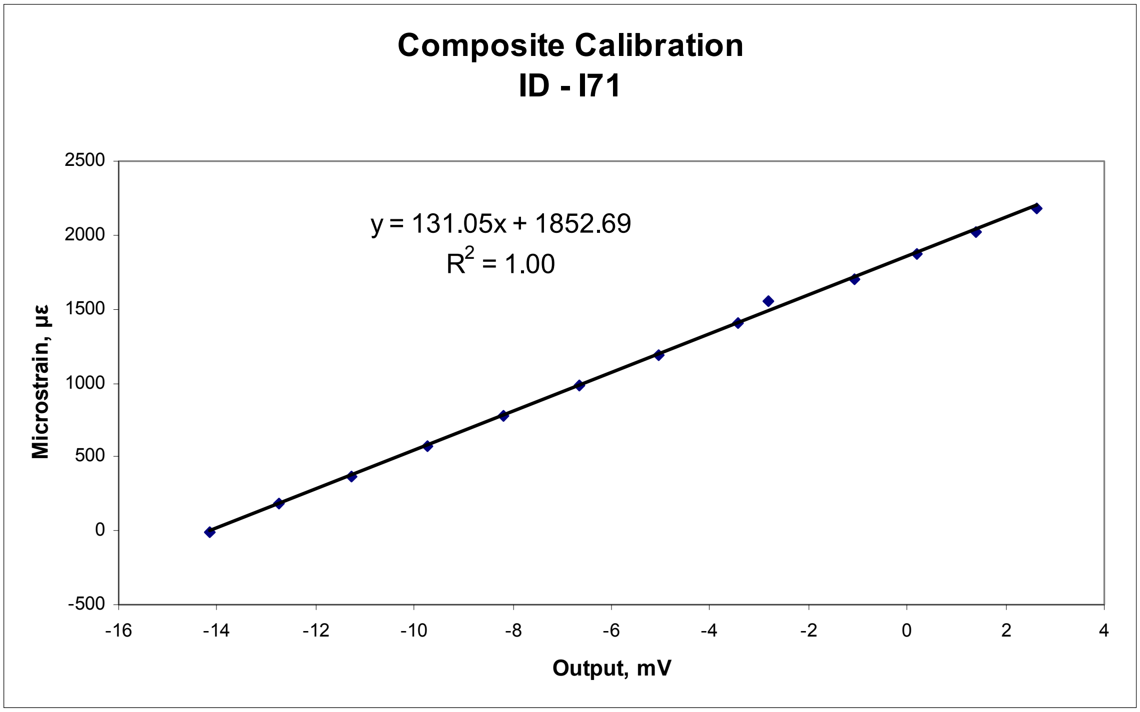


Figure A-5 - CTL gauge I71/A4

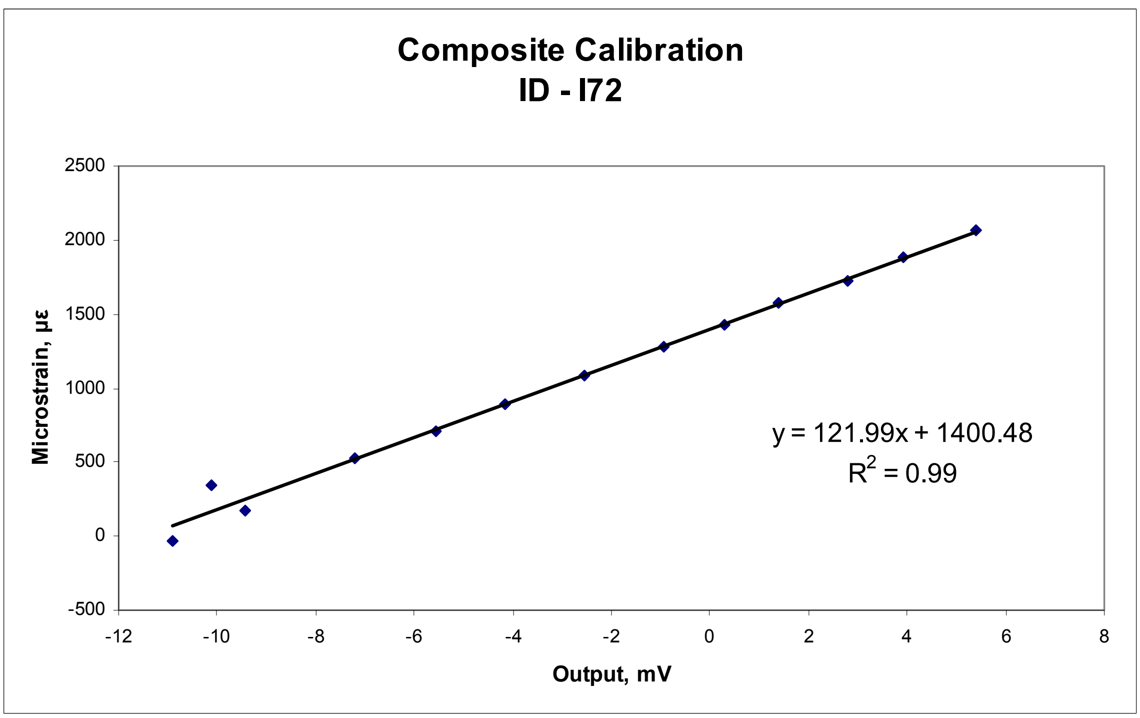


Figure A-6 - CTL gauge I72/A5

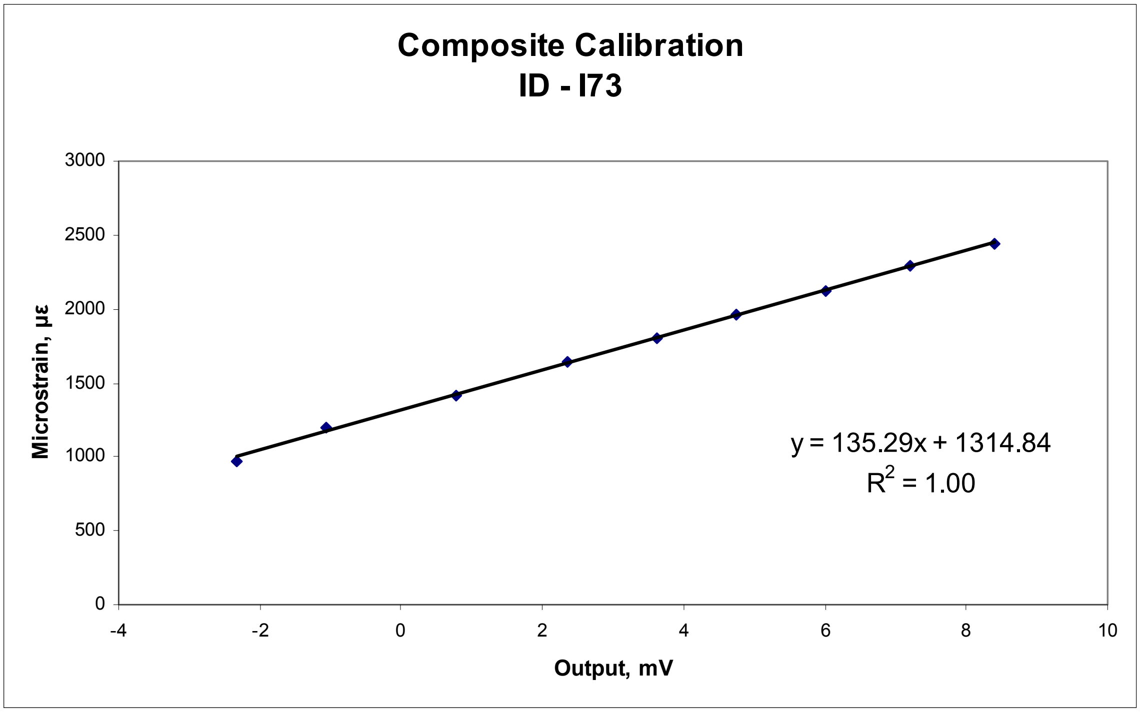


Figure A-7 - CTL gauge I73/A6

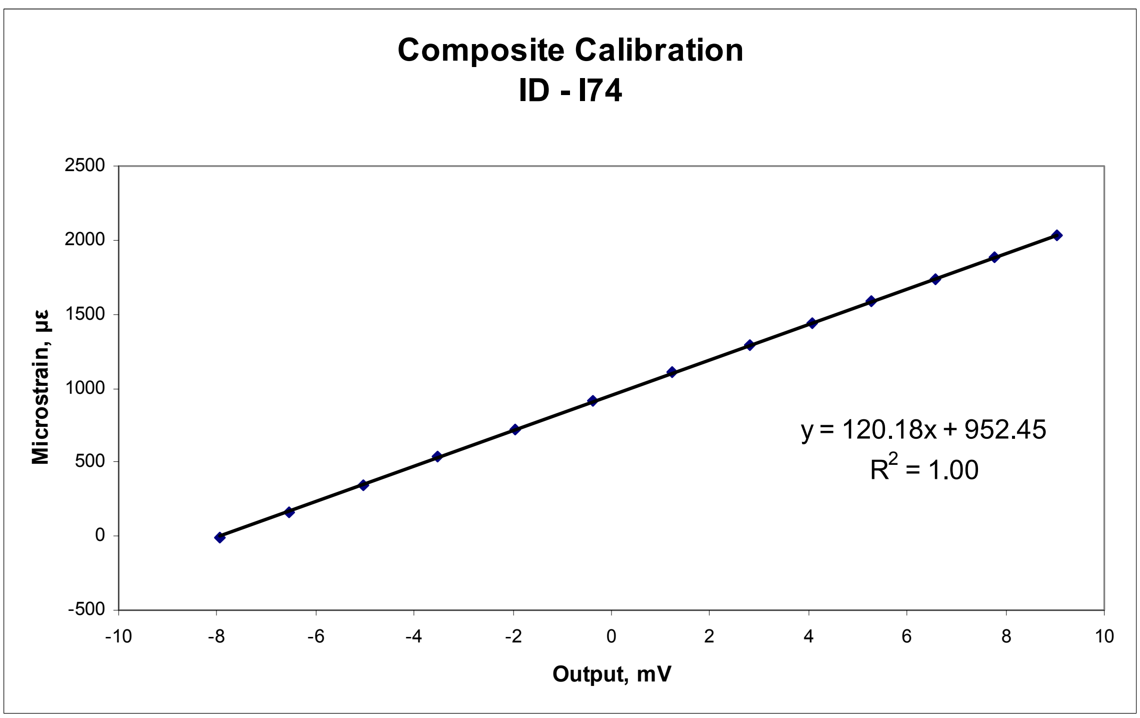


Figure A-8 - CTL gauge I74/A7

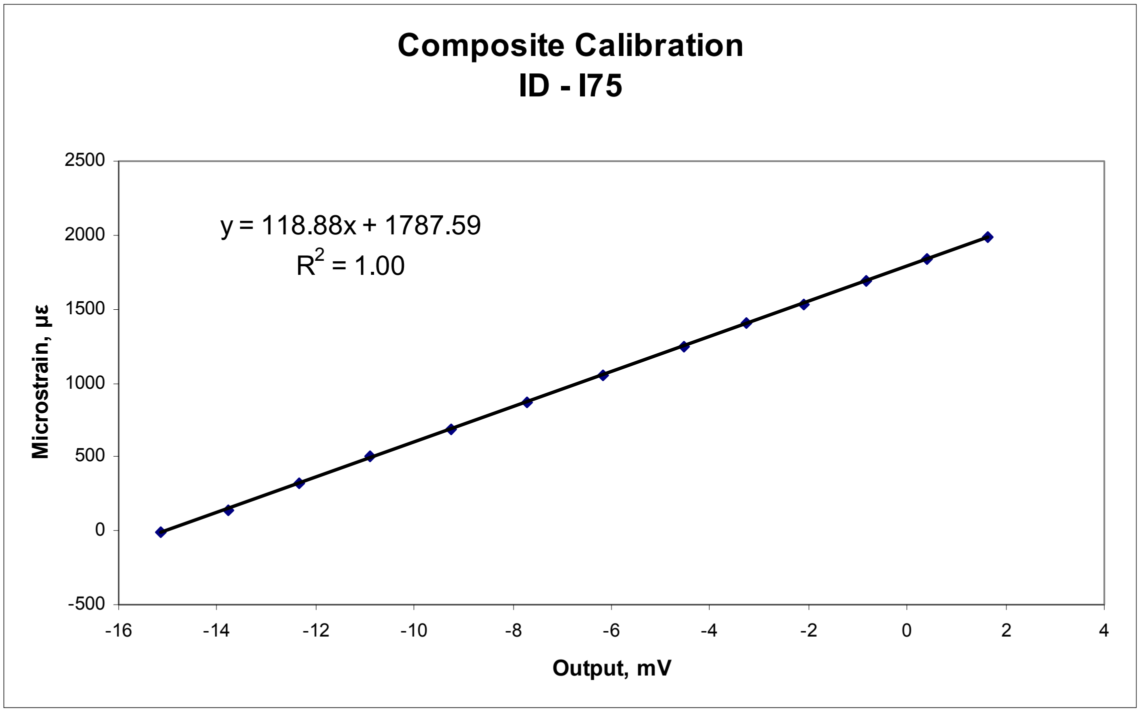


Figure A-9 - CTL gauge I75/B0

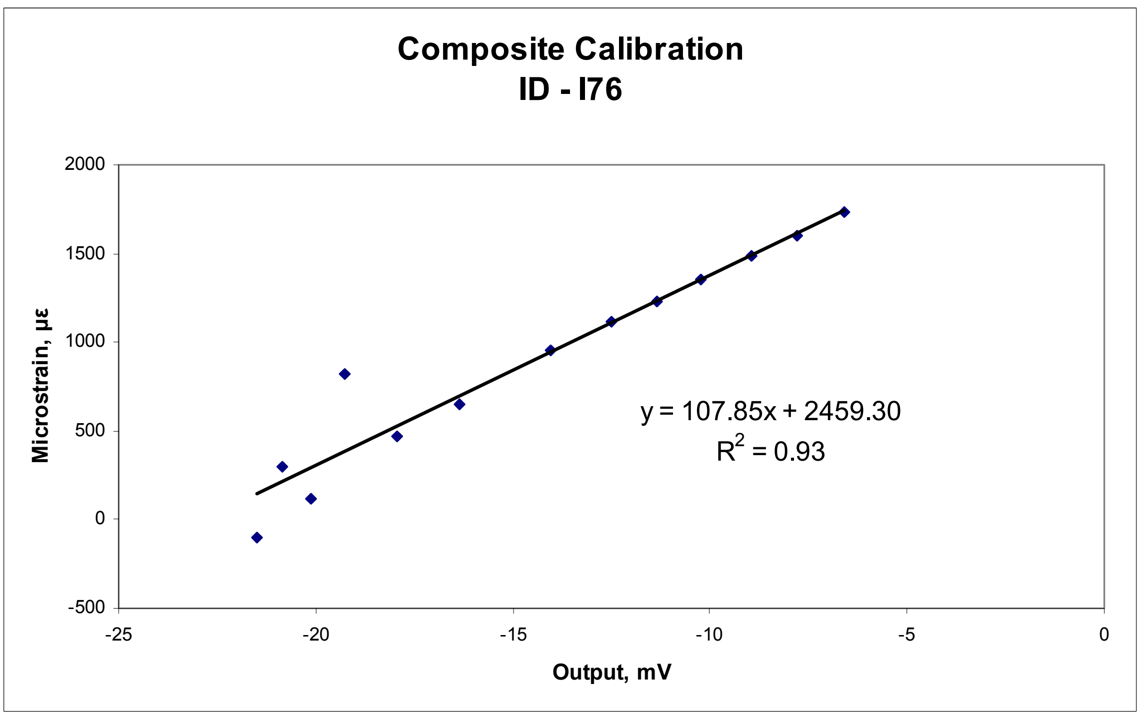


Figure A-10 - CTL gauge I76/B1

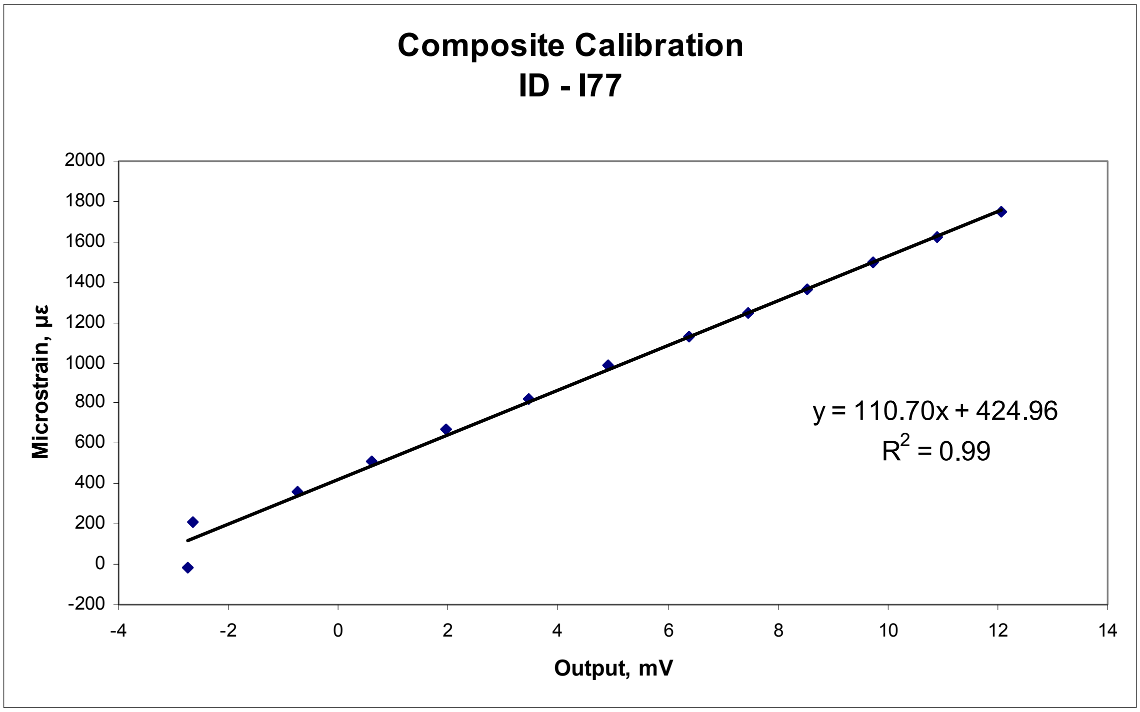


Figure A-11 - CTL gauge I77/B2

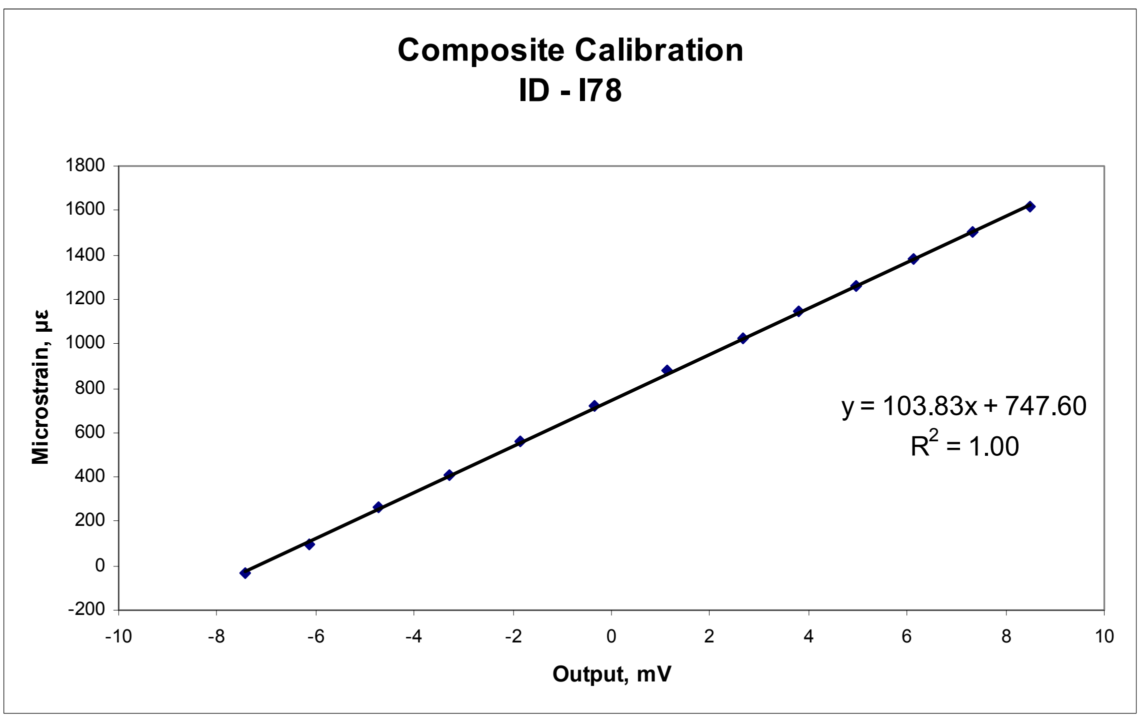


Figure A-12 - CTL gauge I78/B3

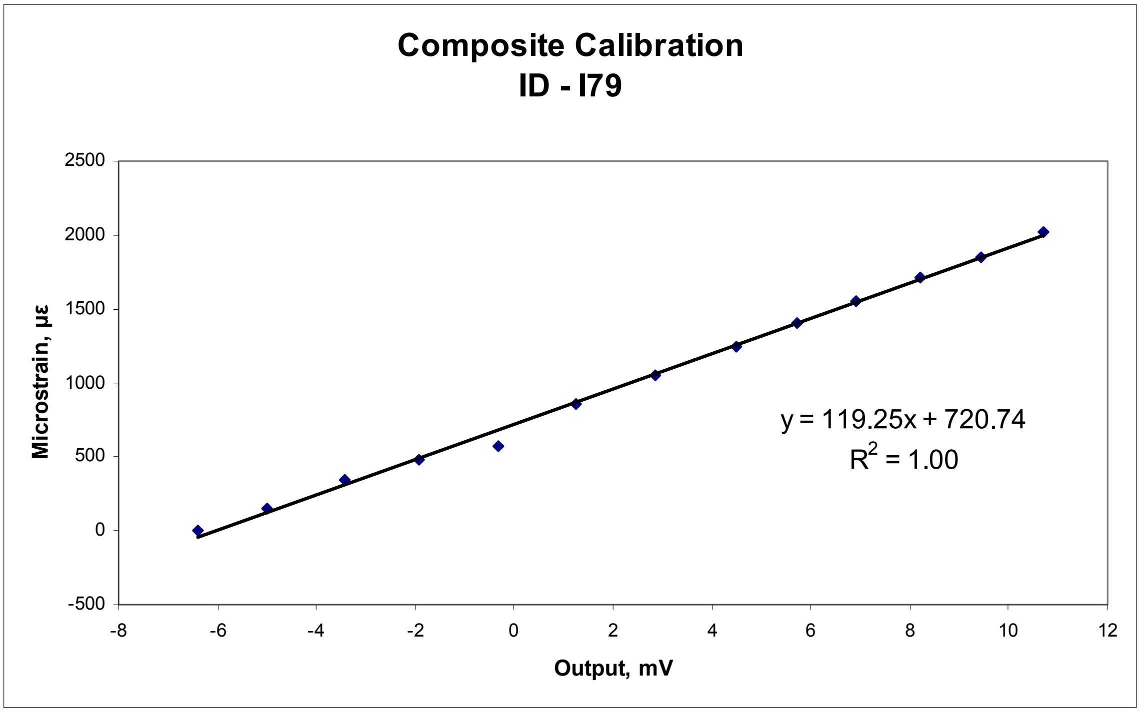


Figure A-13 - CTL gauge I79/B4

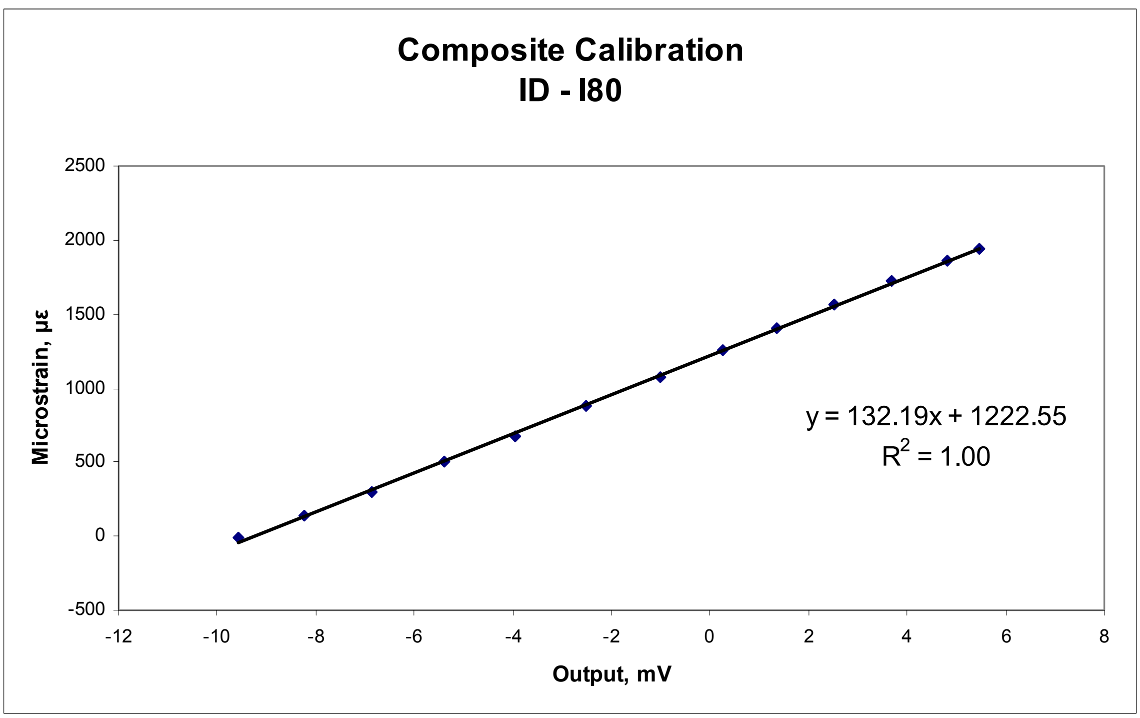


Figure A-14 - CTL gauge I80/B5

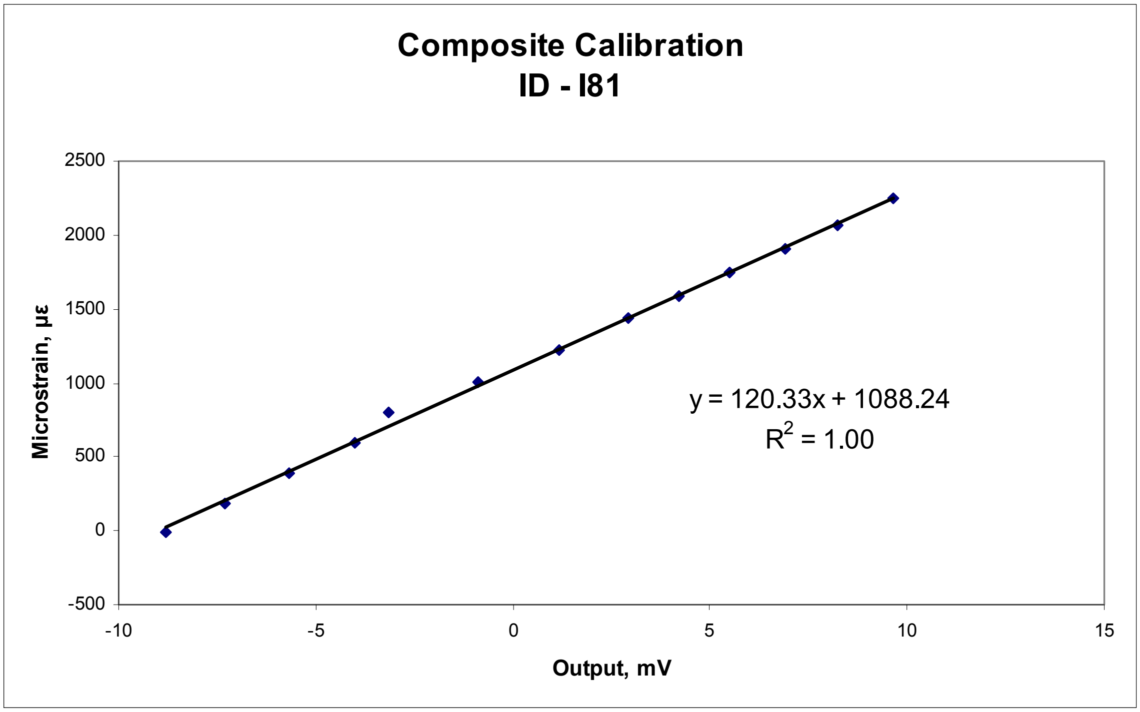


Figure A-15 - CTL gauge I81/B6

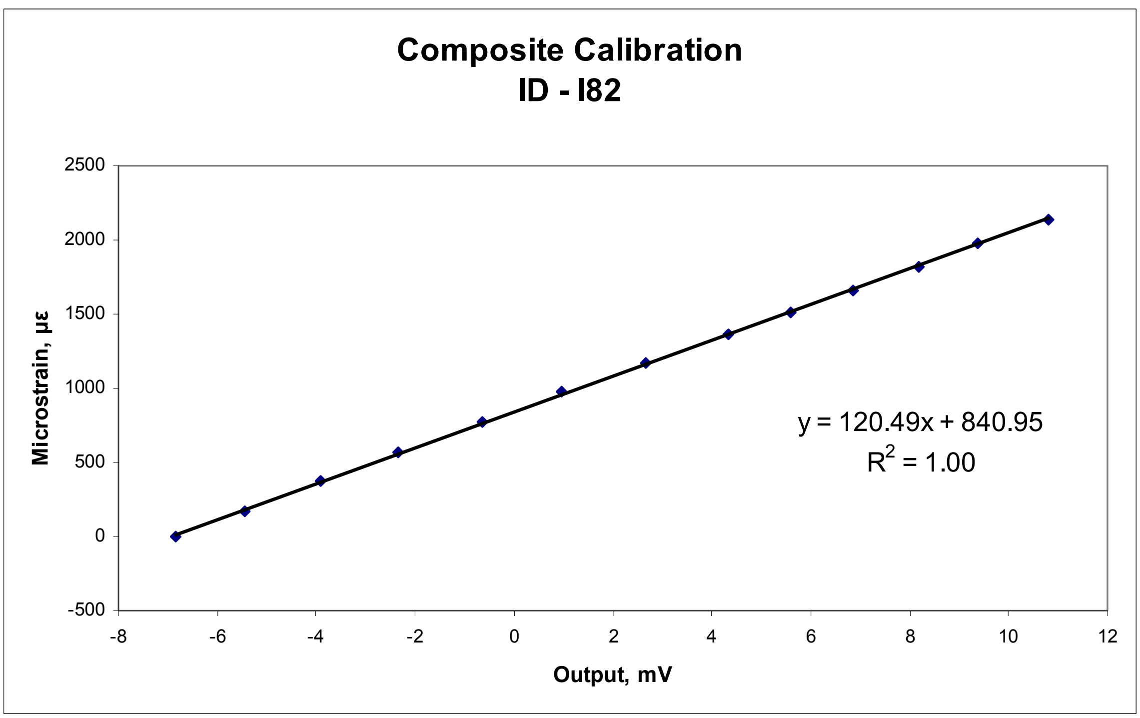


Figure A-16 - CTL gauge I82/B7

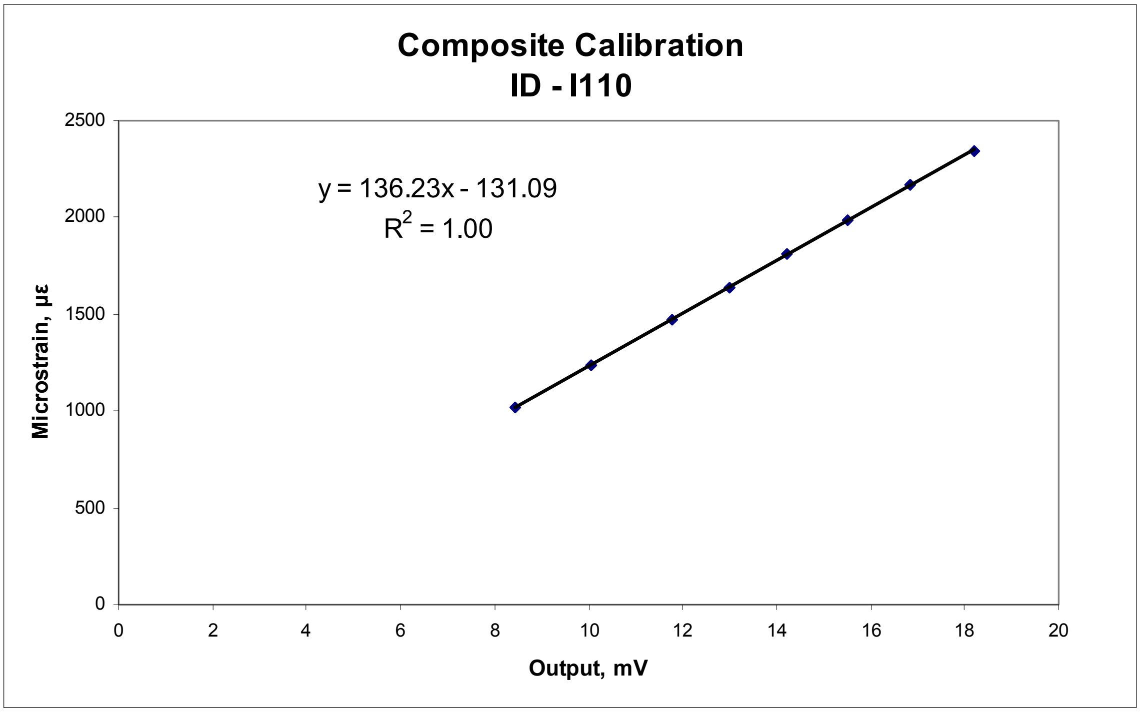


Figure A-17 - CTL gauge I110/D5

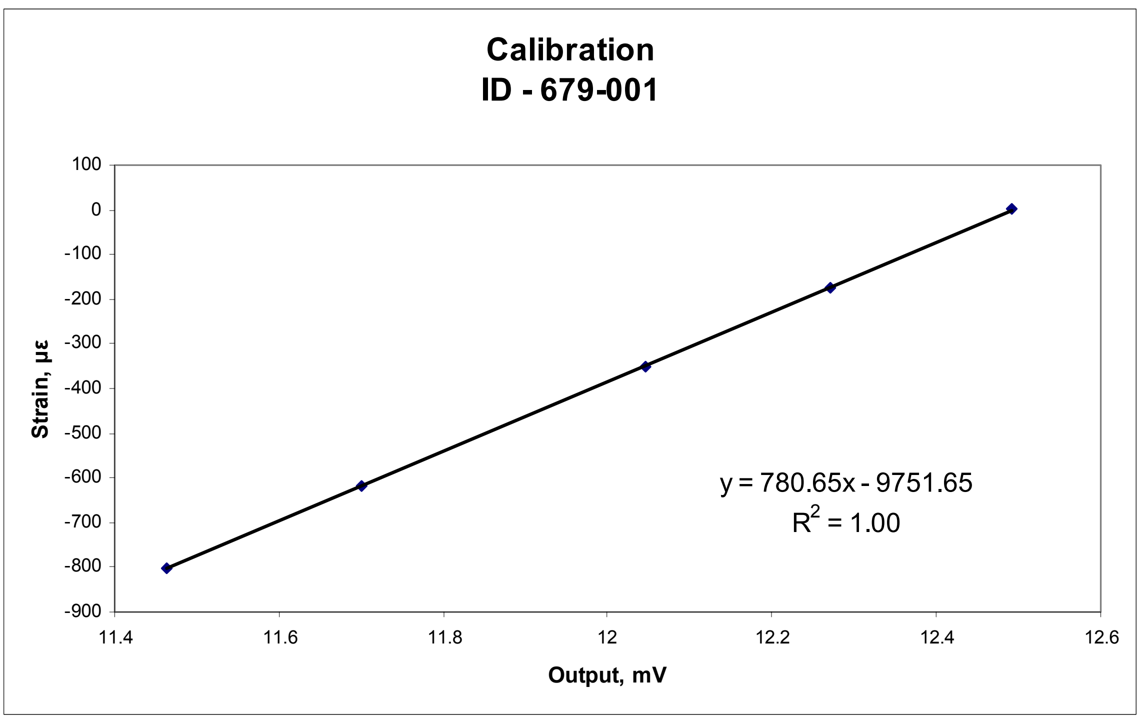


Figure A-18 - Dynatest gauge 679-001/C0

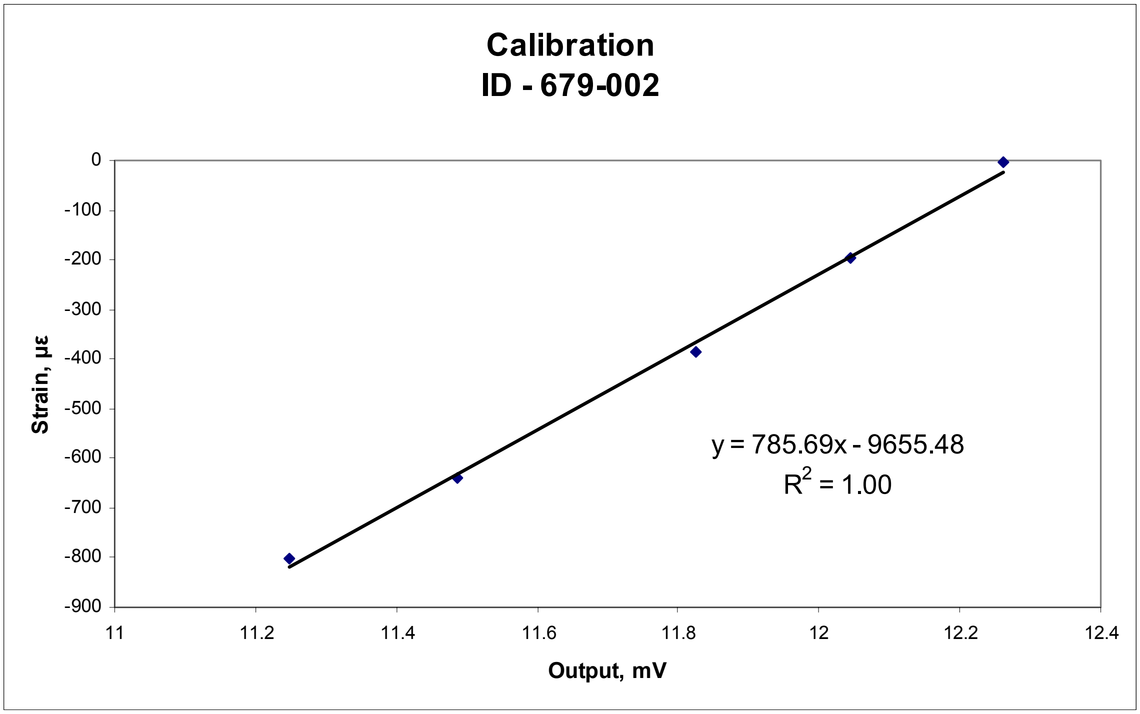


Figure A-19 - Dynatest gauge 679-002/C1

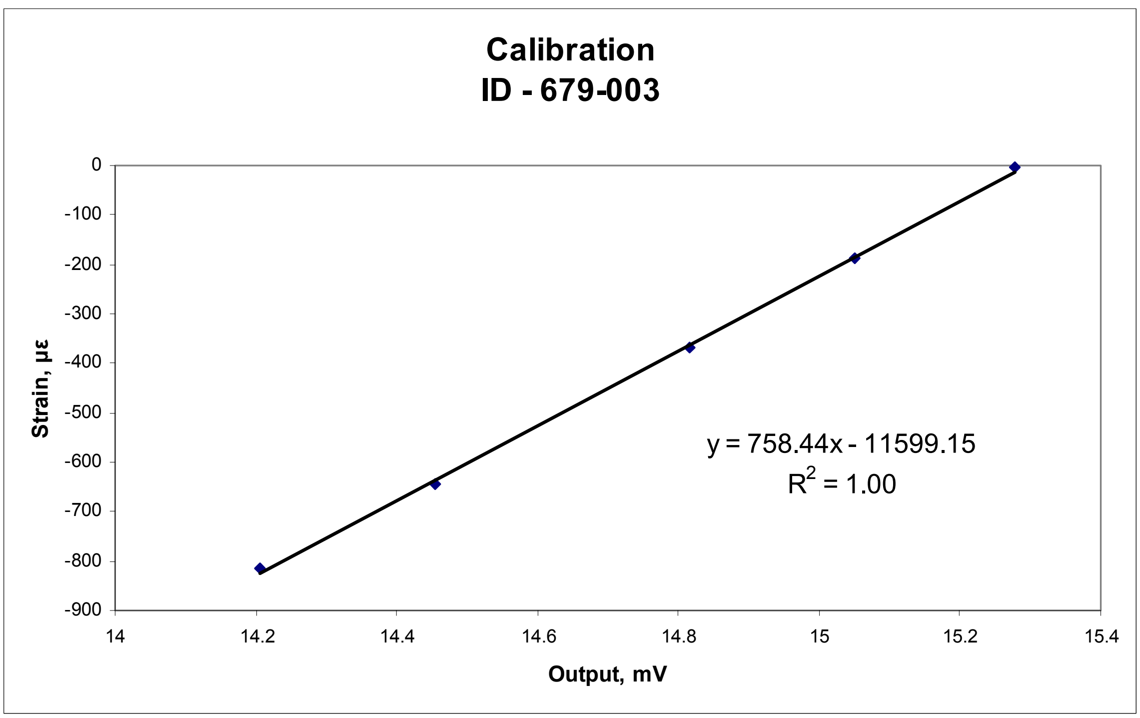


Figure A-20 - Dynatest gauge 679-003/C2

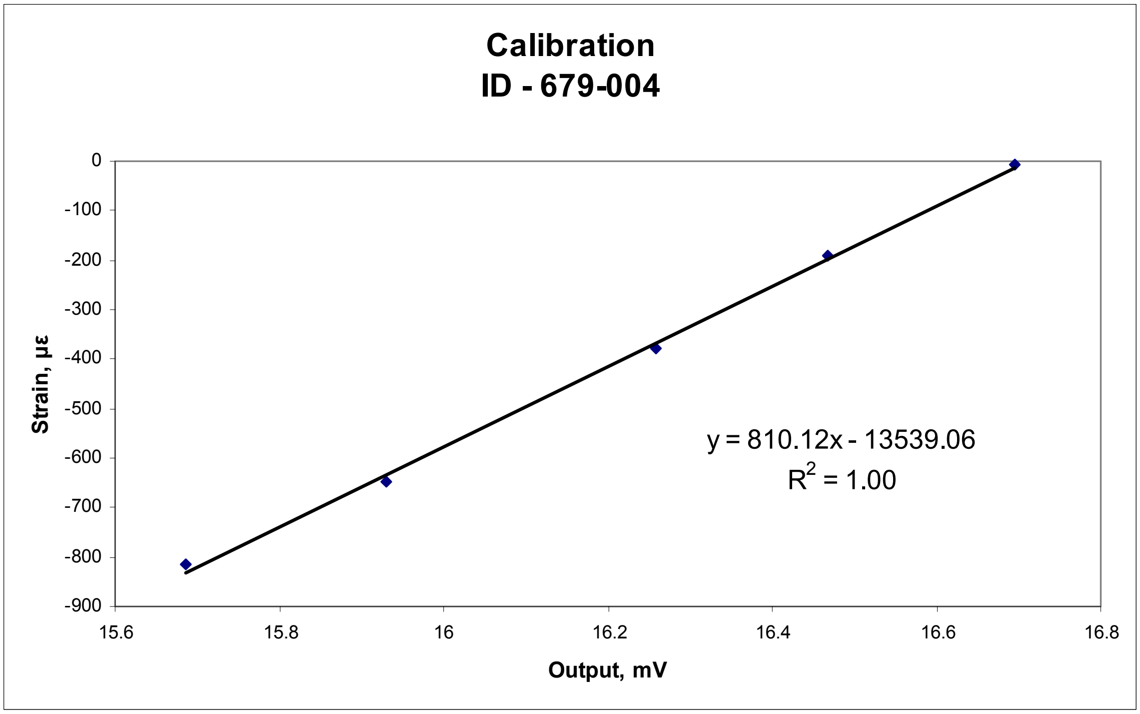
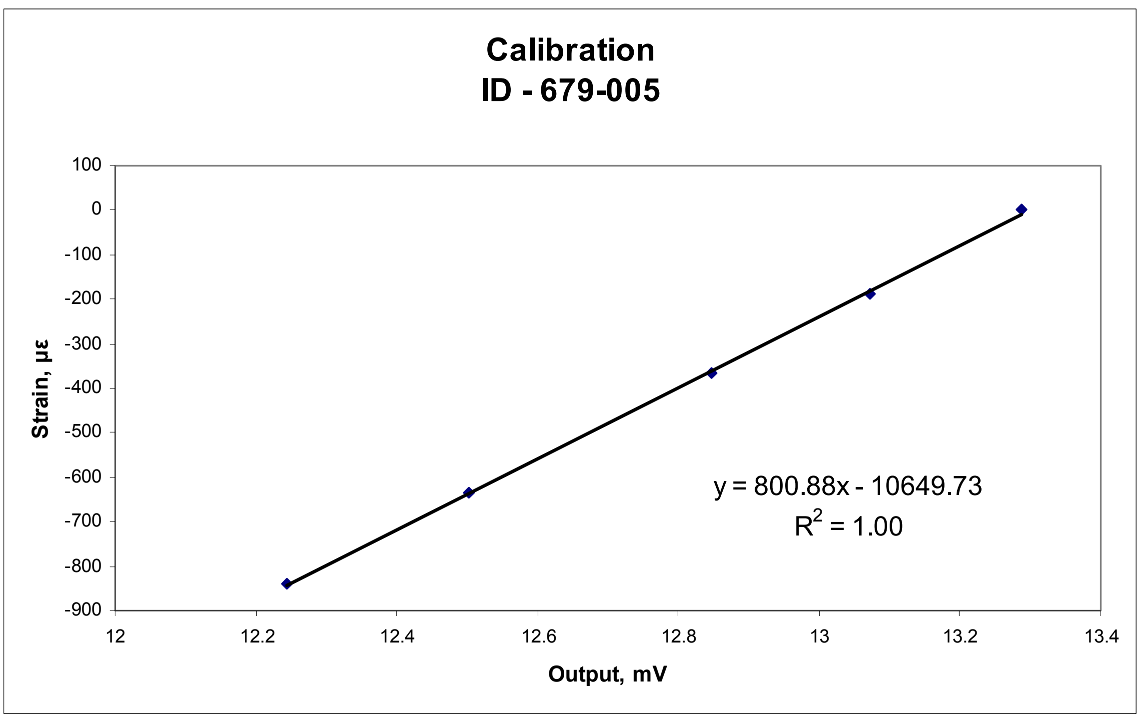


Figure A-21 - Dynatest gauge 679-004/C3



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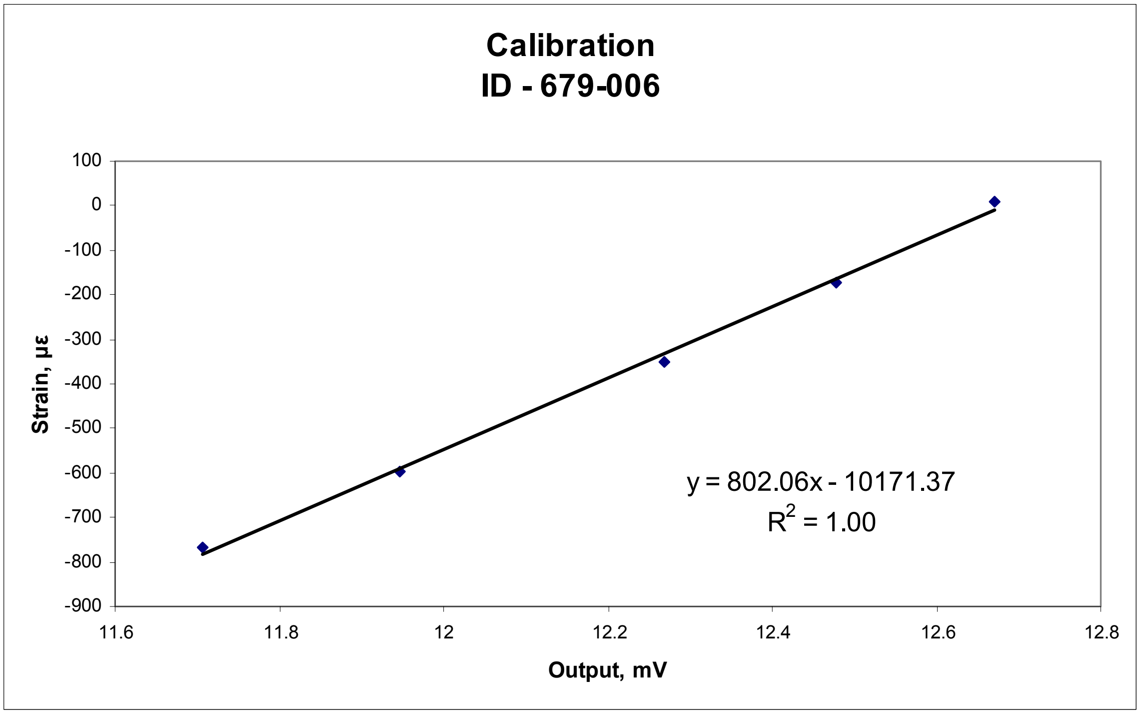

Figure A-23 - Dynatest gauge 679-006/C5

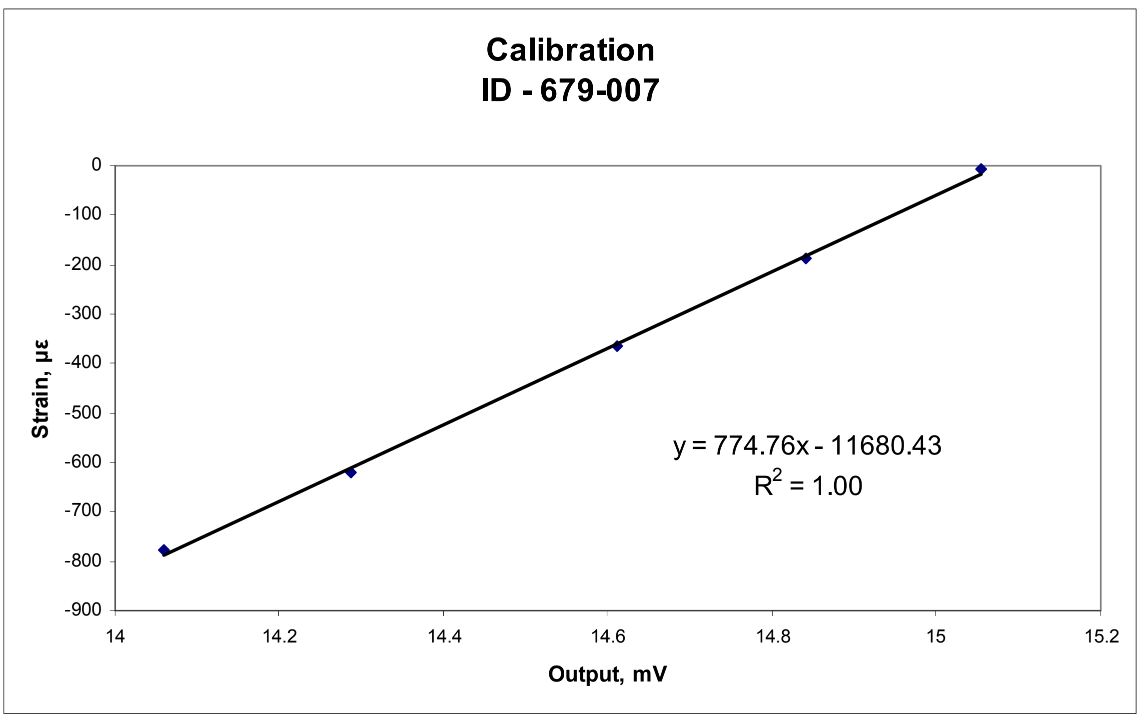

Figure A-24 - Dynatest gauge 679-007/C6

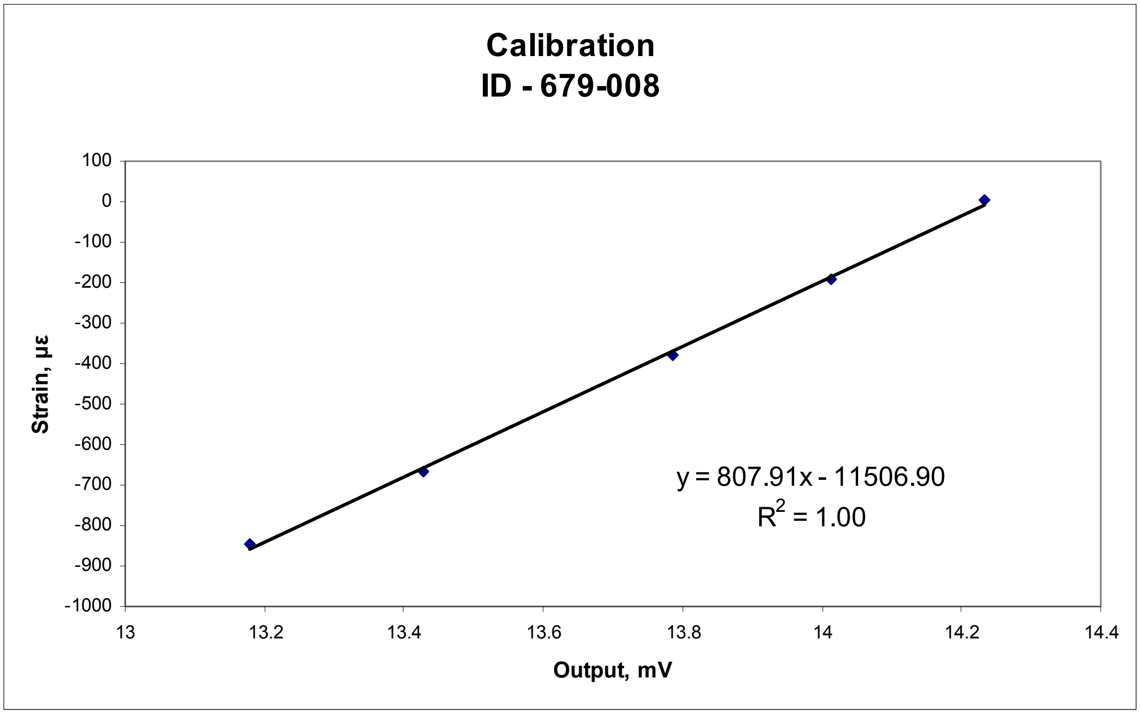

Figure A-25 - Dynatest gauge 679-008/C7

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