Feasibility Study for a Freeway Corridor Infrastructure Health Monitoring Instrumentation Testbed

CFIRE

CFIRE 04-08
August 2012

National Center for Freight & Infrastructure Research & Education
Department of Civil and Environmental Engineering
College of Engineering
University of Wisconsin–Madison

UWM
UNIVERSITY of WISCONSIN
MILWAUKEE

Authors:
Hani Titi, Habib Tabatabai, and Konstantin Sobolev
University of Wisconsin–Milwaukee

Principal Investigator:
Hani Titi, Ph.D., P.E., M.ASCE
Professor, Civil Engineering & Mechanics
University of Wisconsin–Milwaukee

Technical Report Documentation Page

1. Report No. CFIRE 04-08	2. Government Accession No.	3. Recipient's Catalog No. **CFDA 20.701**
4. Title and Subtitle **Feasibility Study for a Freeway Corridor Infrastructure Health Monitoring Instrumentation Testbed**		5. Report Date August 2012 6. Performing Organization Code
7. Author/s Hani Titi, Habib Tabatabai, and Konstantin Sobolev, UW0Milwaukee James Crovetti and Chritopher Foley, Marquette University		8. Performing Organization Report No. **CFIRE 04-08**
9. Performing Organization Name and Address National Center for Freight and Infrastructure Research and Education (CFIRE) University of Wisconsin-Madison 1415 Engineering Drive, 2205 EH Madison, WI 53706		10. Work Unit No. (TRAIS) 11. Contract or Grant No. **DTRT06-G-0020; 242k771**
12. Sponsoring Organization Name and Address Research and Innovative Technology Administration U.S. Department of Transportation 1200 New Jersey Ave, SE Washington, D.C. 20590		13. Type of Report and Period Covered **Final Report [8/1/10 – 7/31/12]** 14. Sponsoring Agency Code
15. Supplementary Notes **Project completed for USDOT's RITA by CFIRE.**		

16. Abstract

With current and near-term construction activities within the freeway system of Southeast Wisconsin, there is a unique opportunity to develop a detailed understanding of their in-service performance by implementing a health monitoring network that can serve as a living laboratory for the State of Wisconsin. Data from this health monitoring network can be used to develop and guide maintenance and inspection operations for these and other critical infrastructure components across the State. This monitoring network can also become a model for the nation, illustrating the benefits and cost savings from an integrated, proactive maintenance program.

17. Key Words Health Monitoring, Infrastructure, Wisconsin, maintenance	18. Distribution Statement **No restrictions. This report is available through the Transportation Research Information Services of the National Transportation Library.**		
19. Security Classification (of this report) **Unclassified**	20. Security Classification (of this page) **Unclassified**	21. No. Of Pages 256	22. Price **-0-**

Form DOT F 1700.7 (8-72) **Reproduction of form and completed page is authorized.**

DISCLAIMER

Feasibility Study for a Freeway Corridor Infrastructure Health Monitoring (IHM) Instrumentation Testbed

Hani H. Titi, Ph.D., P.E., M.ASCE
Habib Tabatabai, Ph.D., P.E., S.E.
Konstantin Sobolev, Ph.D.

Department of Civil Engineering and Mechanics
University of Wisconsin-Milwaukee
3200 N. Cramer St.
Milwaukee, WI 53154

And

James Crovetti, Ph.D.
Christopher M. Foley, Ph.D., P.E., M.ASCE

Department of Civil, Construction & Environmental Engineering
Marquette University
P.O. Box 1881
Milwaukee, WI 53201

Table of Contents

List of Figures

List of Tables

Acknowledgement

This research project is financially supported by Wisconsin Department of Transportation (WisDOT) and National Center for Freight & Infrastructure Research & Education (CFIRE).

The research team would like to thank Mr. John Corbin for his support and guidance during the various phases of this project. The help of Mr. Todd Szymkowski is greatly appreciated. The research team would like to thank the project panel members for their guidance and input during the panel meetings: Mr. Travis McDaniel, WisDOT; Mr. Wesley Shemwell, FHWA; Mr. Finn Hubbard, HNTB; Mr. Kevin McMullen, WCPA; Mr. Ahmet Demirbilek, WisDOT; and Mr. Scot Schwandt, WAPA. During the work on this project, various companies and individuals were contacted and provided technical information/data.

The research team would like to thank Mr. Greg Waidly and CFIRE team for their support and help.

The help of Ms. Michelle Schoenecker in editing the report is greatly appreciated. The effort of graduate students at UWM Andrew Druckrey, Emil G. Bautista, Vahid Alizadeh, and Joe Barritt is acknowledged. The input of Mr. Jay Schabelski, MU is acknowledged.

ABSTRACT

This research discusses the forward-planning necessary for the proper development, acquisition, installation and maintenance of an effective health monitoring network for transportation infrastructure systems. A comprehensive literature search was conducted, in which literature materials pertaining to health monitoring of transportation infrastructure were identified, collected, and compiled into a database. The collected literature materials were reviewed and synthesized. Information on the state-of-the-art in sensors and data acquisition systems, and their applications in infrastructure health monitoring was presented. Focus was placed on sensor technologies that are applied to monitor strain, displacement, acceleration, pressure, load, temperature, corrosion, crack propagation, and scour in various transportation infrastructure systems such as bridges, pavements, and retaining walls. Case histories on instrumentations of bridges, pavements, and geotechnical structures for the purpose of health monitoring were also presented. Moreover, cost analysis and estimates were presented for IHM system components (e.g., sensors, data acquisition), installation, maintenance, data storage, and data processing.

Implementation of an infrastructure health monitoring plan will allow for the collection of data that can be beneficial for future designs of similar structures, during the construction of structures, and during the service life and maintenance of structures. Data elements vital for maintaining safe and functional transportation infrastructures were identified and discussed for bridge structures, pavements, and geotechnical structures. Moreover, the steps necessary for planning an instrumentation system for a particular structure are presented.

Sample design plans for the transportation infrastructure systems that are typically constructed in Wisconsin were obtained from the Wisconsin Department of Transportation (WisDOT). These plans were used to create three-dimensional (3-D) images of various structures including bridges, pavements, retaining walls, bridge pier, and pile bent. Suggested instrumentation plans were developed for these transportation systems and presented on the 3-D images. For a particular structure, the following were identified and implemented on the 3-D images of that structure: data elements to be acquired, types of sensors, number of sensors, locations and orientations of sensors, and data acquisitions and transmission systems.

One of the objectives of the research project was to identify urban freeway construction projects that could efficiently serve as hosts as an IHM instrumentation testbed. Communications with WisDOT and discussion with the project panel resulted in the identification of the following current/future major transportation infrastructure construction projects: the I-94 North-South freeway construction project, the Zoo Interchange reconstruction project, the I-90/I-39 expansion/reconstruction project, the US-41 WI 441 tri-county freeway project, and the Hoan Bridge deck reconstruction project. These projects were critically evaluated to identify a candidate project to host the IHM testbed. Among the listed projects, the Zoo Interchange reconstruction project is recommended for hosting the infrastructure health monitoring testbed.

The 3-D plans developed for IHM of bridge structures, pavements, and geotechnical structures were forwarded to companies with expertise in installing/manufacturing infrastructure health monitoring systems and components to obtain cost estimates. The presented IHM plans, along with the evaluation conducted and the corresponding cost estimates, provide useful information for implementing a freeway corridor infrastructure health monitoring instrumentation testbed.

Archived data from the Marquette Interchange Instrumentation Project was utilized to develop vehicle wander patterns and load spectra data, both in the form needed to conduct a mechanistic appraisal of the pavement structure using the DARWin ME software. Additional data from the wheel wander and the weigh-in-motion (WIM) sensors was collected and analyzed to confirm the viability of using the lower cost piezo sensors for WIM applications integral to IHM projects.

The research team designed an IHM survey questionnaire to learn the current state of practice of highway agencies in the U.S. and Canada. The survey was conducted by e-mail and phone calls after contacting each highway agency to identify engineers who can answer the survey questions. Forty nine State DOTs in the U.S. and 13 Ministries of Transportation (MOTs) in Canada were contacted to answer the survey questionnaire. Out of the 49 State DOTs, six agencies did not respond to the request of the research team (California, Massachusetts, Nevada, New Mexico, Tennessee and West Virginia). Wisconsin was not included in the survey. All Canadian MOTs submitted answers to the survey questionnaire. The answers and collected information were compiled into spreadsheet files to facilitate data analysis and presentation in graphical format. In addition, the answers were analyzed using Map Viewer software in order to present the individual State DOT response to the survey questions. The survey showed that health monitoring applications for transportation infrastructure is being implemented by 46% of State DOT's. The survey identified the impediments facing State DOT's in implementing IHM systems, which included the cost and data analysis and utilization. State DOT's that have utilized IHM systems were satisfied with the results and indicated that they would continue using similar or improved systems in the future.

Chapter 1
Introduction

1.1 Problem Statement

The safe and efficient movement of freight on any mode of transport requires an infrastructure that is well designed, well-constructed, and well maintained. The design and construction of Wisconsin's transportation infrastructure has been, and continues to be, completed in a responsible and cost-efficient manner. However, while well-intended, infrastructure maintenance is often designed and implemented in a stop-gap reactive manner, rather than as part of an organized, planned, proactive infrastructure preservation program. This reactive approach is necessary due to a lack of detailed information on the past, current, and near-future structural/functional health of the infrastructure components.

The Zoo Interchange, the I-94 E/W corridor and the I-794 / Hoan Bridge are all vital components of the Southeast Wisconsin surface transportation infrastructure network. The aged and structurally compromised Zoo Interchange structures were recently replaced to provide adequate support for the passing heavy truck loads; however, these replacements were temporary stop-gap measures to maintain serviceability prior to the complete redesign/reconstruction of this interchange. A portion of I-94 E/W, running from 35th Street in Milwaukee County to STH 16 in Waukesha County, was also recently resurfaced to enhance the safety and functionality of this heavily trafficked corridor. Complete reconstruction of the Zoo Interchange is scheduled for 2015 – 2018.

The I 794 / Hoan Bridge project will maintain connectivity between downtown Milwaukee and the Port of Milwaukee. The project includes bridge replacements between the Milwaukee River and the Lake Interchange and a deck replacement of the Hoan Bridge. This construction is expected to begin in the Fall of 2013.

1.2 Research Project

With current and near-term construction activities within Southeast Wisconsin's freeway system, there is a unique opportunity to develop a detailed understanding of its in-service performance by implementing a health monitoring network that can serve as a living laboratory for the State of Wisconsin. Data from this health monitoring network can be used to develop and guide maintenance and inspection operations for these and other critical infrastructure components across the state. It also has the potential to become a model for the nation, illustrating the benefits and cost savings from an integrated, proactive maintenance program.

There are several phases in the life of any major component of Wisconsin's transportation infrastructure system: planning, design, construction, maintenance, and decommissioning. With each passing day, the performance reliability of the system is reduced. Ultimately, the State is faced with making periodic investments in maintenance and inspection operations designed to gain additional service life or to simply maintain the originally expected service life. Data describing the in-service condition of an infrastructure component is critically important during this maintenance phase.

Current and future tools can give the State real-time infrastructure performance information that, if assembled and warehoused correctly, can become an integral component of cost-effective maintenance operations. Remote sensing and wireless technology can preclude the need for short-duration visual inspection cycles because the infrastructure component can continually relay what it is "seeing" without the need for manual inspections–this reduces inconvenience to the motoring public, precludes the need for inspectors to conduct what often amounts to very dangerous work, and reduces operating expenses. There is a need to start acquiring data from the time a critical piece of infrastructure first goes into full service; if this data is available, optimal allocation of fiscal and human resources for target performance and reliability levels can occur.

Southeast Wisconsin has three major research universities poised and ready to address this challenging research initiative: University of Wisconsin-Milwaukee, Marquette University, and the Medical College of Wisconsin. The expertise and leadership of these three institutions in infrastructure research and planning can be leveraged to help develop a living health monitoring network for critical components of the surface transportation infrastructure in Wisconsin. This network will be important to the economic well-being of the State and will illustrate responsible use of the limited fiscal resources needed for maintenance and inspection operations while enhancing the safety and convenience of the motoring public for decades to come. The system will accommodate interim (e.g., resurfacing) and ultimate (e.g., reconstruction) corridor lifecycle horizons, and use the findings to guide ultimate maintenance and repair strategies.

The development and implementation of an integrated health monitoring network can provide new tools for infrastructure system design and maintenance in Wisconsin; in other words, the health monitoring testbed can be the seminal investment Wisconsin makes for the future. Another important benefit of this research is the synergistic activity between three leading colleges in the State, each of which plays an important role in training tomorrow's engineers.

1.3 Research Objectives

This research effort represents the forward-planning necessary for the proper development, acquisition, installation, and maintenance of a dynamic health monitoring network for transportation infrastructure systems. The collaboration of university faculty will provide leadership and education in state-of-the-art systems for health monitoring and maintenance of infrastructure components, with an emphasis on stimulating changes to design policy and more effectively dispersing the state's fiscal and human resources for maintaining infrastructure components and systems. There are several immediately apparent outcomes that can result from such a laboratory. An interchange/corridor health monitoring network can be used for real-time acquisition of (among other things):

a. Stress ranges for fatigue assessment and assignment of inspection frequency
b. Strain acquisition for periodic monitoring of the impact of vehicle loads on critical portions of the infrastructure
c. Monitoring the intrusion of de-icing chemicals into the bridge deck and potential deterioration
d. In-situ measurement and quantification of load paths through critical components of the interchange superstructure
e. Monitoring the impact of thermal movement and associated strains induced into the infrastructure components throughout its service life
f. Use the interchange/corridor as a testbed for new technologies for health monitoring with subsequent evaluation and recommendations for implementation elsewhere in Wisconsin’s infrastructure network
g. Monitoring traffic operations (volumes, loadings, crashes, incidents)
h. Monitoring the roadside environment (noise, drainage, air quality)

1.4 Research Report

This report summarizes the state-of-the-art information for the design, installation, operation, maintenance and costs of infrastructure sensors and data collection/transmission equipment.

This report is organized in ten chapters. Chapter One presents the problem statement and objectives of the study. Background information on the development of Infrastructure Health Monitoring (IHM) concept, benefits, and challenges are presented in Chapter Two. Chapter Three identifies the components of IHM. Chapter Four presents case histories on IHM. Cost analysis and estimates of IHM are summarized in Chapter Five. Chapter Six identifies and evaluates candidate urban freeway construction projects for hosting the testbed. Infrastructure health monitoring plan for the Zoo Interchange is presented in Chapter Seven. Example of utilizing IHM data in pavement applications is depicted in Chapter 8. Chapter Nine presents the results of an IHM survey of highway agencies in the U.S. and Chapter 10 presents the conclusions and recommendations of the study.

Chapter 2

Structural Health Monitoring

2.1 Background

Generally, Structural Health Monitoring (SHM) is referred to as the implementation of methods for evaluating the condition of a structure based on a combination of observation, measurements, analysis, and modeling (Rice and Spencer, 2009). SHM evolution is attributed to the development of Nondestructive Evaluation (NDE) methods to assess damage and evaluate the condition of materials and structural components in industrial and aerospace fields. Development of NDE methods, such as acoustic emission in the 1970s and the advancement in NDE technologies and analysis in 1980s, have led to the acceptance and use of NDE methods. Djordjevic (1990) presented NDE methods and discussed their use and significance in inspection and maintenance of space structures before, during, and post-launch. While NDE methods focus on assessing the damage of materials and structural components on a "local" level, SHM has evolved as a separate field with a "global" focus on assessing infrastructure conditions (Rice and Spencer, 2009). Currently, SHM is associated with sensing technologies and applications.

2.2 Definition

The SHM concept is generally defined in relation to sensor-based detection and monitoring of damage in infrastructure. Sohn et al. (2004) presented an extensive review of SHM and its applications to aerospace, civil, and mechanical engineering infrastructure. Sohn et al. (2004) defined SHM as the process of implementing a damage detection strategy for aerospace, civil, and mechanical engineering infrastructure. Sohn et al. (2004) and Farrar and Worden (2007) defined damage as changes introduced to a system (e.g., bridge) that have an adverse impact on the current and future performance of the system. Sohn et al. (2004) indicated that damage definition requires a comparison between two different states of the system, one of which is the initial (undamaged) state. When describing damage to structural systems, Farrar and Worden (2007) defined damage as changes to the material and/or to the geometric properties of the system, to boundary conditions and to system connectivity, which has an adverse impact on the performance of the system. Damage does not necessarily mean the total loss of system serviceability; in fact, it may indicate a reduced level of system performance. Increased levels of damage may bring the system to a state of failure when the system no longer operates in an acceptable manner according to its users.

Sohn et al. (2004) characterized damage in terms of length and time scales. Based on length scales, damage begins on the material level (local level) and progresses to component and system (global) levels at different rates, depending on the physical and environmental loading conditions on the system. In terms of time, damage accumulation occurs gradually in cases such as fatigue and corrosion. In addition, damage can occur instantaneously (short-term) in cases of structures subjected to extreme events such as earthquakes and vessel collision with bridge structures in waterways.

Liu (2008) defined SHM as the process of determining and assessing the nature of damage in a structure. According to Liu (2008), SHM of civil infrastructure consists of determining (using measurements) the location and severity of damage in infrastructure. DeWolf et al. (2006) indicated that the continuous operation of instrumented structural health monitoring systems can be used to supplement visual inspections of bridges and the possible detection of damage.

As defined by Balageas et al. (2006), SHM "aims to give, at every moment during the life of a structure, a diagnosis of the "state" of the constituent materials, of the different parts, and of the full assembly of these parts constituting the structure as a whole." SHM comprises sensors, smart materials, data transmission, computational power, and processing units allocated within the structures, as schematically presented in Figure 2.1.

To detect and monitor damage, SHM systems use sensing technologies to observe the behavior of a structure/system by collecting and communicating real-time data/measurements of its materials and geometric properties. Detecting and monitoring changes to materials and geometric properties can be analyzed to identify damage/failure or other adverse impacts on system performance. The process of analyzing (making sense) of collected data is perhaps the most important, but sometimes neglected, component in an SHM system.

Farrar et al. (2007) defined SHM through the following statistical pattern recognition paradigm:

(i) Operational evaluation
(ii) Data acquisition, normalization and cleansing
(iii) Feature selection and information condensation
(iv) Statistical model development for feature discrimination

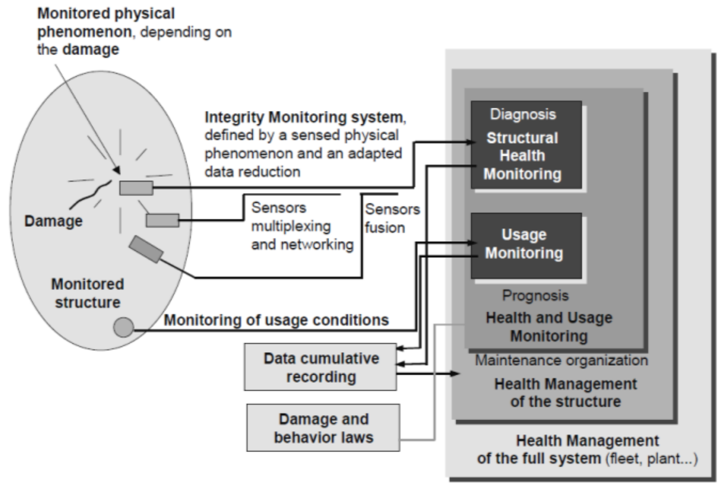


Figure 2.1: Principle and organization of a SHM system (Balageas et al., 2006).

Farrar and Worden (2007) presented a detailed discussion of their four-step process, as summarized below:

Operational evaluation: The following points must be addressed in relation to damage detection/identification via SHM:

1. Benefits of implementing SHM systems in terms of life savings and cost reduction
2. Damage definition for the system under consideration and the most important damage type in case more than one damage type occurs
3. Identification of operational and environmental conditions under which the system functions
4. Limitations of collecting data under the operational environment

Data acquisition, normalization, and cleansing: One of the SHM processes is to acquire data from sensors, which includes selecting the sensor excitation method, sensor types, number, locations, the data acquisition, data storage, and data transmittal hardware. Farrar and Worden (2007) defined data normalization as the process of separating the sensor-reading data measured as a result of damage from data recorded from the operational and environmental conditions of the structure. Data cleansing is defined as a knowledge-based process in which data is selected or rejected from inclusion in the database of collected measurements.

Feature selection and information condensation: Part of the SHM process in which the acquired data measurements are condensed and analyzed to allow for damage identification, i.e., to differentiate between damaged and undamaged structure.

Statistical model development: Part of the SHM process in which statistical models are developed to discriminate between damaged and undamaged structures.

Rytter (1993) proposed a five-step process to describe the state of damage for a system in which the following questions must be answered:

(i) Existence. Is there damage in the system?
(ii) Location. Where is the damage in the system?
(iii) Type. What kind of damage is present?
(iv) Extent. How severe is the damage?
(v) Prognosis. How much useful life remains?

2.3 Benefits of Structural Health Monitoring (SHM)

As lifelines of Wisconsin's economy, the infrastructure systems' health and maximized utility affects the livelihood of all citizens. Just as a physician relies on monitoring systems to properly assess, diagnose, and treat patients, those tasked with preserving the State's infrastructure systems must rely on accurate information to guide their decisions.

Structural health monitoring of infrastructure systems has many short- and long-term benefits to a wide range of stakeholders. It is beneficial to planning and maintenance personnel, as it provides objective information for efficient and timely decision making. It is beneficial to the taxpayers, as timely information can lead to improved safety, and the efficiency of maintenance decisions can lead to cost savings. Finally, this is also beneficial to the university and research community, as it provides a wealth of information and data for research that promotes future improvements in design and maintenance methods.

Obtaining relevant, reliable, and accurate information is a first step in an effective health monitoring system; however, such information must also be communicated effectively and be readily accessible to users. Such information also must be accompanied by proper data synthesis, which can lead to actionable and meaningful inferences. There are, however, many parameters for which proven methods of measurement are not yet available; therefore, it is important that statewide structural health monitoring programs also include a separate "testbed" component, in which new and innovative sensors and monitoring systems developed by companies and universities can be field-tested.

2.4 Challenges to Infrastructure Health Monitoring

There are many challenges to successful implementation of SHM. The first challenge involves design and planning of SHM. The objectives of the program must be balanced against the needed scope and cost. Optimized and minimized sensor locations, types, and numbers, long wired distances (when applicable), power supply and communication systems in remote project locations, and protection against vandalism pose significant challenges in planning and design. Design must also consider traffic control and protection of the structure after sensor installation.

However, the main impediment to the widespread and effective use of SHM historically has been the lack of emphasis and focus on the interpretation and analysis of data collected to arrive at conclusions useable by decision makers. Most of the focus is placed on the technological development of modern sensor hardware and advanced data acquisition systems; however, collecting significant quantities of sensor readings without the embedded ability to decipher information to meaningful conclusions has been a drawback to some SHM systems.

Chapter 3

Architecture of SHM System

3.1 Background

The SHM system consists of the following components: power supply, sensors, protection of hardware in the field, data acquisition and control, communication systems (wired and/or wireless), data access, sharing, and storage, and data synthesis and reporting.

When the sensor detects damage or change of the parameter of interest (e.g., stress, environmental condition), it sends a signal (generally electric) to the acquisition and storage units (Figures 3.1 and 3.2); alternatively, the response from the sensor network can be surveyed on demand or within certain time intervals. The data transferred from the sensor network(s) are multiplexed, converted to digital signal (A/D conversion) and delivered by the dedicated channels (wire/wireless lines) to the monitoring unit, and analyzed by the expert system vs. the previously registered data and the knowledge based on damage mechanics and the principles of material/structural behavior.

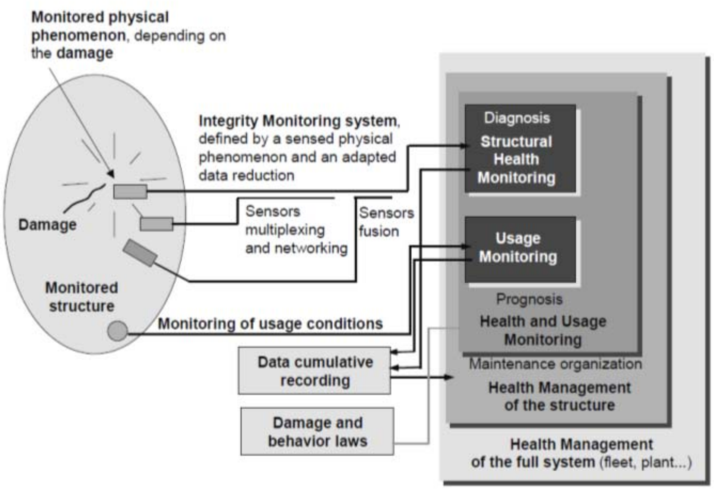


Figure 3.1: Principle and organization of a SHM system (Balageas et al., 2006).

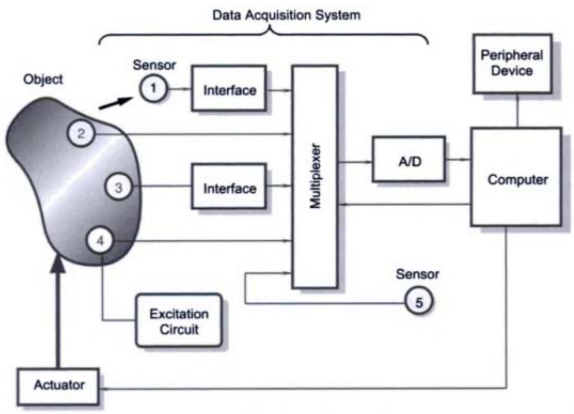


Figure 3.2: Positions of sensors in data acquisition system (Fraden, 2004).

3.2 Sensors

A sensor is an instrument that measures physical quantity or responds to change in physical parameters by transmitting a resulting signal that can be interpreted by an operator or device. The following section describes several sensors that are useful for monitoring the health of a transportation infrastructure.

Strain Gages

A strain gage is a sensor that measures the strain of an object at the attachment point. Strain gages can be used to measure other parameters such as load and pressure when incorporated into load cells and pressure cells. The following are types of strain gages:

1. Vibrating Wire Strain Gages (VWSG): Measure the vibration frequency of a wire element under tension. Strains are related to the measured frequency of vibration of a wire within the gages; as strain increases, the frequency of vibration increases. Vibrating wire gages are not suitable for dynamic (rapid) strain measurements. Types of VWSGs are weldable or embedded in concrete. Weldable VWSGs can be attached to steel surfaces through a special welding device. Adhesives are not used for attaching such gages. Embedded VWSGs are used (embedded) within plastic concrete to measure internal concrete strains. VWSGs can be obtained from Applied Geomechanics, Geokon, Slope Indicator, RST Instruments, Smartec, Encardio Rite, and HBM. Figure 3.3 shows various VWSGs.

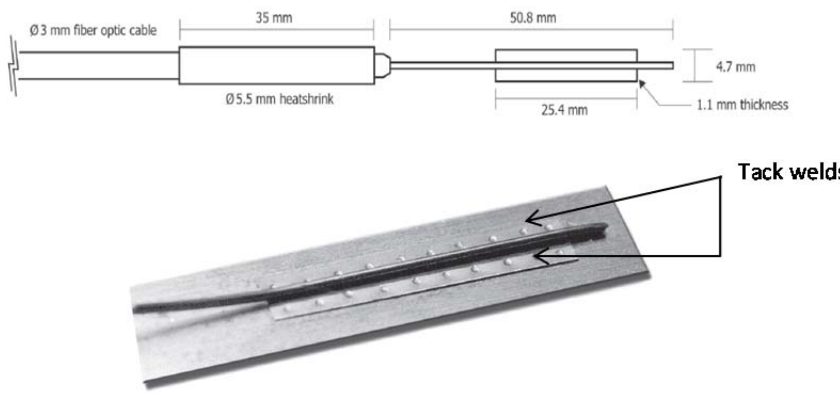
2. Electrical Resistance Strain Gages (ERSG): A length change (strain) in a resistance-type strain gage results in a change in its electrical resistance, which can be measured through a Wheatstone bridge. Strain is proportional to the change in resistance of the gage. These devices are relatively inexpensive (approximately $5-$10 each) and are

applied to the test surface by adhesives. Readout devices can be simple bridge completion and balancing stand-alone units or multi-channel data acquisition cards. Electrical resistance strain gages can be monitored at high speed using appropriate data acquisition hardware. Types of ERSGs include bonded wire, unbonded wire, bonded foil, semiconductor, and weldable strain gages. Bonded wire strain gages are discrete metal or silicon strain gages that are usually bonded (glued) to the surface where the strain is to be measured, providing an output proportional to the average strain in their active area. Unbonded strain gage transducers use relatively long strands of strain gage wire stretched around posts attached to a linkage mechanism. The bonded foil strain gage is the most popular type of resistance strain gage, in which the metal is attached firmly to a strong flexible insulating transparent sheet; that sheet in turn is bonded by epoxy to the material whose strain is to be measured. Semiconductor strain gages are made of semiconducting silicon and have a larger gage factor that makes them more sensitive to strain. Weldable resistance strain gages can be tack-welded to steel surfaces using special welding hardware. ERSG can be obtained from Vishay, Micro Measurements, Omega, Micro Sensor Technology, Endevco Corp., and Micron Instruments. Figure 3.4 depicts various types of electrical resistance strain gages.

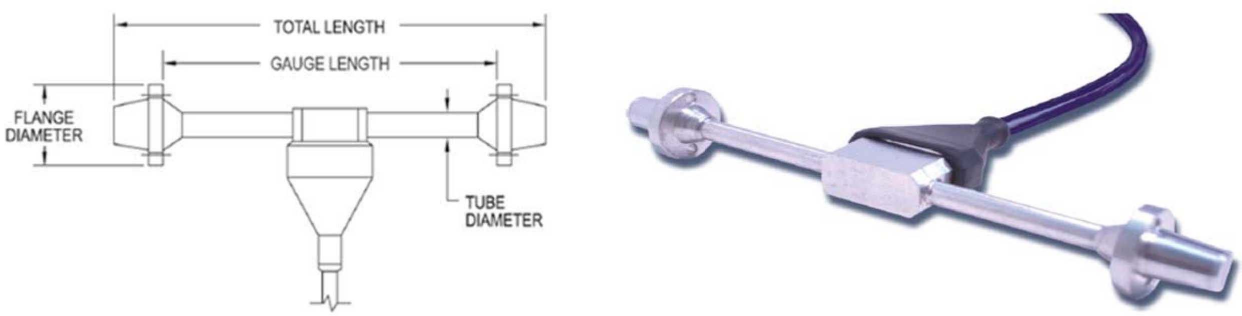
3. “Sister” Strain Gages or Rebar Strainmeters: Designed to measure strains within concrete (embedded). Typical applications include measuring strain in bridge girders, concrete piles, tunnel linings, mass concrete structures, and retaining walls. These consist of resistance strain gages attached to a piece of reinforcing bar, which can be embedded in concrete. Manufacturers of “sister” strain gages include Geokon, Applied Geomechanics, Marton Geotechnical Services, LTD, and RST Instruments. Figure 3.5 shows pictures of various strain gages.

4. Distributed Fiber Optic Strain Gage: Consists of a long optical fiber that can be attached or embedded in structures. There are discrete sensing points at fixed intervals along the fiber; therefore, multipath measurements can be made along the length of the same fiber. Fiber optic strain gages are designed for environments where it may be difficult to use conventional types of strains gages because of space considerations or high levels of electrical interference. Manufacturers of distributed fiber optic strain gages are Geokon and Applied Geomechanics. Figure 3.6 shows a picture of a distributed fiber optic strain gage.

(a) Vibrating Wire Strain Gages (http://www.rstinstruments.com)

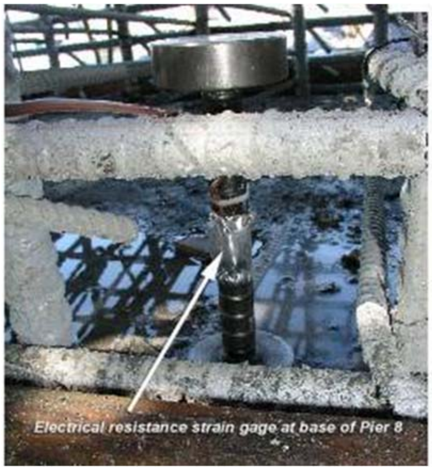


(b) Weldable Vibrating Wire Strain Gage (http://smartec.ch)

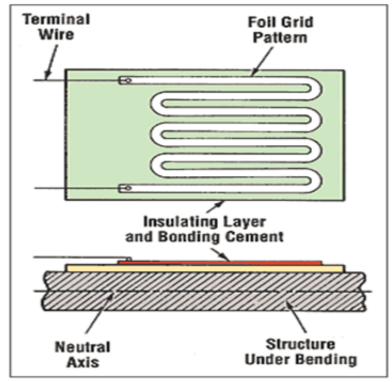


(c) Embedded Vibrating Wire Strain Gage (http://smartec.ch)

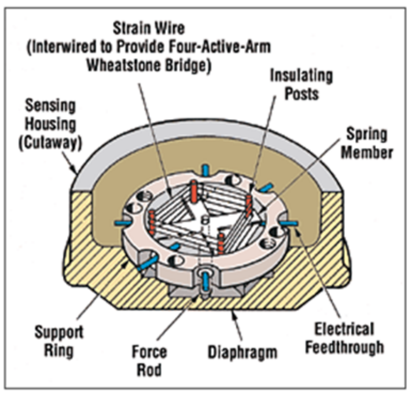
Figure 3.3: Various type of vibrating wire strain gages.



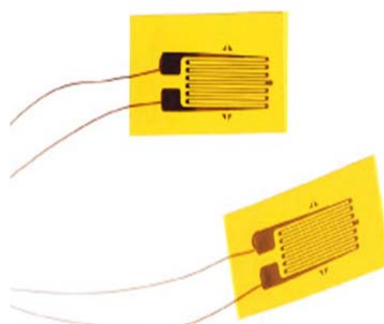
(a) Electrical Resistance Strain Gage (http://cee.engr.ucdavis.edu/)



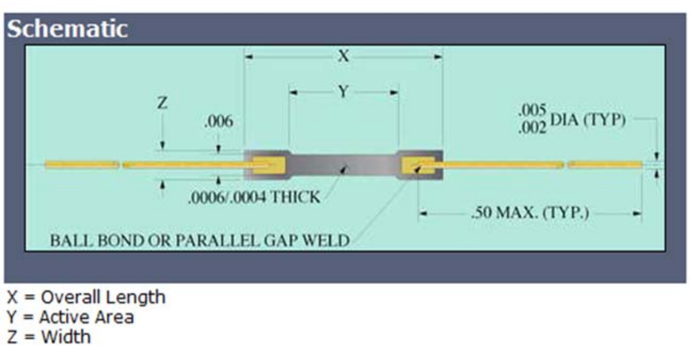
(b) Bonded Wire Strain Gages (http://www.sensorsmag.com)



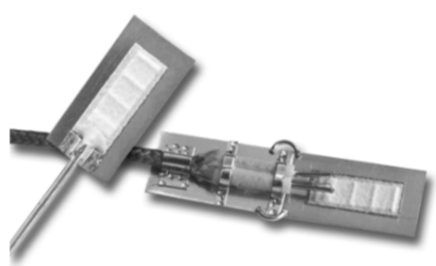
(c) Bonded Wire Strain Gages (http://www.sensorsmag.com)



(d) Typical Metal Foil Strain Gages (http://www.omega.com)



(e) Schematic of a Bar-Shaped Semiconductor Strain Gage (http://www.microninstruments.com)



(f) Weldable Strain Gages. (http://www.vishaypg.com)

Figure 3.4: Types of electrical resistance strain gages.

Figure 3.5: Vibrating wire rebar strain meter (below) and vibrating wire sister bar (above) (http://www.rstinstruments.com)

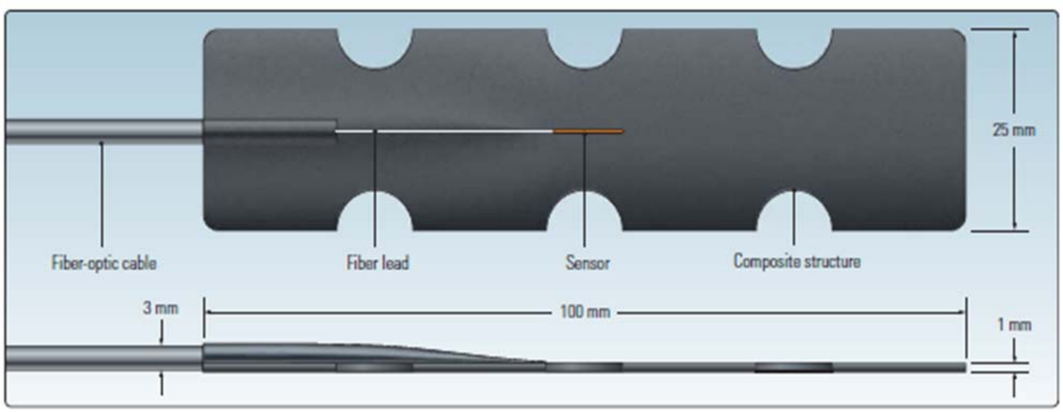


Figure 3.6: Distributed fiber optic strain gage (http://www.geokon.com).

There are many strain sensors based on fiber optics (Lopez-Higuera 2002, Livingston 2002), Table 3.1. Fiber Optics Sensors (FOS) have some advantages over conventional electronic sensors such as compact size (50-130 microns), ruggedness to interference with electromagnetic radio frequency, immunity to lightning strikes, zero drift, self-referencing capabilities, and elimination of fire hazard in enclosed spaces (Livingston 2002). Fiber optics sensors with a Bragg diffraction grating on the fiber are commonly used for measuring strains (Livingston 2002), especially for monitoring highway bridges (Hughs et al. 2005; Idriss et al. 1998, Livingston 2002). When light of the near-IR range (1,510 – 1,590 nm) is transmitted through the fiber, the diffraction grating reflects back a specific critical wavelength, CW. If a strain is applied to the grating area, the spacing of the Bragg grating changes, which affects the wavelength of the CW; in turn, such shift in wavelength can be converted to a strain change, Figure 3.7 (Todd et al. 1999, Livingston 2006). An advantage of the FBG technique is that multiple sensors can be applied along a single fiber, thereby reducing the cable installation costs (Livingston 2006).

Table 3.1: Fiber optic strain sensing techniques (Livingston 2006).

Light Property	**Sensing Technique**
Amplitude	Microbend
Reflected pulse travel time	Optical time domain reflectometry
Phase angle	Fabry-Perot interferometry
Diffracted wavelength	Bragg grating
Scattered wavelength	Brillouin (thermal Doppler shift)
Nonlinear scattered wavelength	Raman scattering
Polarization angle	Pressure-sensitive index of refraction

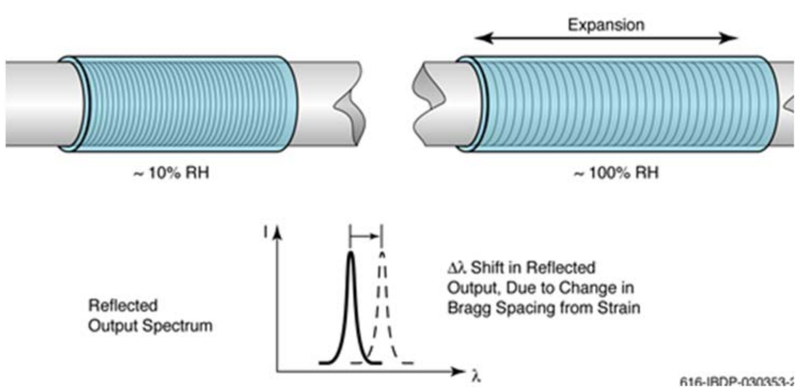


Figure 3.7: Diagram of Fiber Bragg Grating RH Sensing Concept (Livingston 2006).

Accelerometers

An accelerometer is a device that measures the acceleration of an object attached to it. An accelerometer consists of an internal mass, an elastic “spring,” and a controlled level of damping within an enclosure. Accelerometers can be uni-directional (measure in one direction only), two- or three-dimensional. The types of accelerometers include piezoelectric or piezoresistive and seismometers, each having a range of frequency over which it performs as designed. Accelerometers need external power sources and can be monitored with automated data acquisition systems at relatively high speeds. They can be used to measure vibration on specific points or as part of a “modal analysis” of a structure to determine its vibration frequencies and mode shapes, as well as to measure seismic activity, inclination, machine vibration, dynamic distance and speed with or without the influence of gravity.

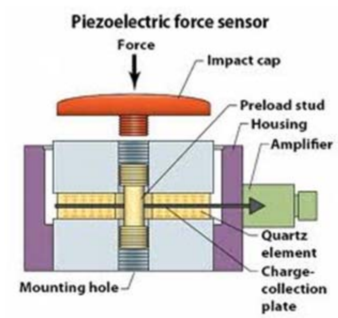
For transportation infrastructure, accelerometers are used to measure the motion and vibration of a structure exposed to dynamic loads. Dynamic loads originate from a variety of sources, including activities from human use, machines working in or near the building, construction work such as driving piles, demolition, drilling and excavating, moving loads on bridges, vehicle collisions, impact loads, concussion loads, internal and external explosions, collapse of structural elements, wind loads and wind gusts, air blast pressure, loss of support due to ground failure, and earthquakes and aftershocks. Measuring and recording how a structure responds to these inputs is critical for assessing the safety and viability of a structure.

1. Piezoelectric Accelerometer: Uses the piezoelectric effect of certain materials to measure dynamic changes in mechanical variables such as acceleration, vibration, and mechanical shock.

2. Piezoresistive Accelerometer (Strain Gage Accelerometer): Measure constant, transient, and periodic acceleration. They may be fabricated from metal strain gages, piezoresistive silicon, or as a MEMS device. In such designs, resistive material is typically bonded to a cantilever beam that undergoes bending under the influence of acceleration. This bending causes deformation of the resistor, leading to a change in its resistance. The resistors are normally configured into a Wheatstone bridge circuit, which provides a change in output voltage that is proportional to acceleration.

3. Seismometers: Measure and record motions in the earth’s crust due to events such as earthquakes or volcanoes. Seismometers can pinpoint and measure the size of such motions that can act on structures.

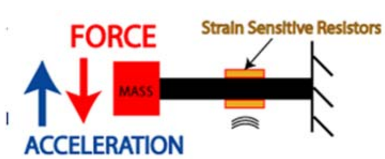
Manufacturers of accelerometers include Endevco, PCB, Bruel & Kjaer, Omega, Wilcoxon Research, ST Microelectronics, and Measurement Specialties. Figure 3.8 show pictures of accelerometers.



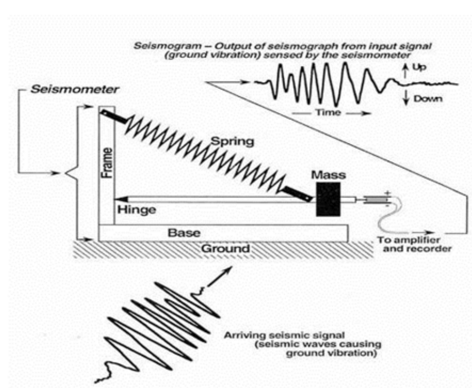
http://images.machinedesign.com

http://www.pcb.com

(a) Piezoelectric Accelerometers



(b) Piezoresistive Accelerometer (http://www.pcb.com)

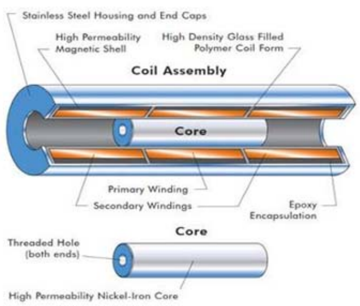


(c) Schematic of a Seismometer (http://web.ics.purdue.edu)

Figure 3.8: Various types of accelerometers

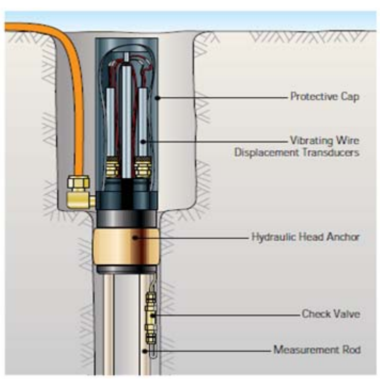
Displacement Transducers

A displacement transducer is a device that relates movement of one of its ends with respect to the other to an electrical signal that can be monitored. Types of displacement transducers include linear variable differential transformer (LVDT), linear pontetiometers, extensometers, crack gages or joint meters, and global positioning systems (GPS). Figure 3.9 shows selected types of displacement sensors.



(a) Features of a Linear Variable Transducer (http://www.sensortips.com)

(b) Linear Pontentiometers (http://www.specsensors.com)



(c) Extensometer

(d) Vibrating Wire Soil Extensometer (http://www.rstinstruments.com).

Figure 3.9: Selected types of displacement sensors.

1. Linear Variable Differential Transducer (LVDT): A type of electrical transformer used to measure linear displacement. The electrical signal changes as a core penetrates into

the magnetic shell of a coil assembly. Manufacturers include Trans-Tek, Geokon, Macro-Sensors, and Measurement Specialties.

2. Linear Pontetiometer: A resistor with a sliding contact that forms an adjustable voltage divider. Potentiometers are widely used as a part of displacement transducers because of their ruggedness, simplicity, and lower cost compared with LVDTs. Manufacturers include Applied Geomechanics.

3. Extensometers: Measure small and large changes in the length of an object. It is useful for stress-strain measurements and tensile tests. Its name comes from "extension-meter." Types include single point, multiple point, tape extensometers, and magnetic extensometers. Manufacturers include Geokon and Applied Geomechanics.

    a. Vibrating Wire Soil Extensometer: Monitors lateral and longitudinal deformation of soil and different types of embankments. Figure 3.9d shows a vibrating wire soil extensometer.

4. Crack Gages or Joint Meters: Crack meters measure change in the width of a surface crack; it is essentially a displacement sensor that measures movements across the two sides of an existing crack. Crack meters can range from simple non-electrical scales, or “scratch gages,” to LVDTs. They are used to monitor cracks in concrete structures, rock, bridges, and pavement slabs. The joint meter is similar to a crack meter, but is ideally suited for measuring the displacement/movement across joints, such as joint opening in a bridge. Crack meters monitor the cracks in concrete structures; rock, soil and masonry structures; and buildings affected due to nearby construction or excavation activity. Joint meters measure mass movement in bridges, tunnels and shaft linings, rock, soil and masonry structures. Manufacturers include Geokon, Geotest, PRG, and Durham Geo Slope Indicator.

5. Global Positioning Systems (GPS): Compute three-dimensional position and movement, and can be operated remotely worldwide. As a satellite-based system, GPS is ideal for monitoring large structures such as bridges, dams, landslides, and land subsidence.

6. Fiber Optic Sensors: Used either as the sensing element ("intrinsic sensors") or as a method to relay signals from a remote sensor to the electronics that processes the signals ("extrinsic sensors"). Depending on the application, fiber may be used for the following reasons: its small size; no electrical power is needed at the remote location; many sensors can be multiplexed along the length of a fiber by using different wavelengths of light for each sensor; or for sensing the time delay as light passes along

the fiber through each sensor. Fibers can be used to measure temperature, pressure, strain, voltage, current, liquid level, rotation, and particle velocity. Manufacturers include Banner, Keyence Measurement Solutions, and MTI Instruments.

Tiltmeters/Inclinometers

Tiltmeters or inclinometers monitor the change in angle (rotation) of surfaces on the ground or a structure. Tiltmeters have been used to monitor building and bridge safety in an attempt to provide forewarning of distress. Tiltmeters applications include monitoring the tilt of retaining walls and monitoring landslides, in which the failure mode can be expected to contain a rotational component. Manufacturers include Geokon, Slope Indicator, and Automation Sensors and Measurement. Figure 3.10 depicts pictures of inclinometers and tiltmeters.

1. Vertical In-Place MEMS (Micro-Electro-Mechanical Systems) Inclinometers: Monitor lateral movements of soil and rock. In-Place Inclinometers (IPI) consist of one or more MEMS inclinometer sensors enclosed in a 1.25 in diameter, water-tight stainless-steel enclosure, as shown in Figure 3.10a. Vertical In-Place MEMS Inclinometers systems monitor soil stability adjacent to excavation or underground work, and monitor deflection of piles, piers, bridge abutments, and retaining walls.

2. Horizontal In-Place MEMS Inclinometers: Monitor underground vertical movement due to construction and excavation and settlement that may occur around tunnels and embankments. Applications include monitoring soil stability adjacent to excavation or underground work and monitoring settlement vertical movement and settlement around tunnels and roadways.

3. In-place MEMS Tiltmeters: Measure tilt in either one or two axial planes perpendicular to the surface of the base plate (uniaxial or biaxial). It is available for installation in either the vertical or horizontal direction. Figure 3.10b depicts an In-Place MEMS Tilt Meter with vertical mounting plate. Applications include monitoring the tilt of retaining walls, landslides, bridge piers, and ground subsidence.

(a) Vertical In-Place MEMS Inclinometer (http://www.rstinstruments.com)

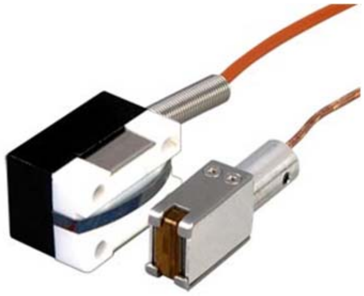
(b) In-Place MEMS Tilt Meter with Vertical Mounting Bracket (http://www.rstinstruments.com)

(c) Tiltmeter (http://www.stoneymiller.com)

Figure 3.10: Inclinometer and tiltmeter.

<u>Temperature Sensors</u>

1. Thermocouples: Thermocouple wires form a junction between two different metals that produces a voltage related to a temperature difference. Thermocouples are widely used for measurement and control and can also be used to convert heat into electric power. Thermocouples can be read using thermocouple readers, or data acquisition systems. Type ‘K’ thermocouples are widely used in industry and have good resistance to oxidation. The operating temperature of type ‘K’ ranges from -269^{o}C to 1,260^{o}C. Type ‘T’ thermocouples are also widely used in all environments. Type ‘N’ thermocouples are generally designed to be used in temperatures up to 1,000^{o}C. Manufacturers include Omega. Figure 3.11 depicts temperature sensors.



(a) Magnetic Mount Thermocouple Probes
(http://www.omega.com)

(b) Surface-Mount RTD
(http://www.omega.com)

(c) Vibrating Wire Temperature Sensor
(http://www.geokon.com/products/datasheets/4700.pdf)

(d) Non-Contact Infrared Sensor Powered via PC
(http://news.thomasnet.com)

Figure 3.11: Various types of temperature sensors.

2. Resistance Temperature Sensors: Also known as RTD, these sensors use the change in electrical resistance of some materials with temperature; they generally have better accuracy than thermocouples.

3. Vibrating Wire Temperature Sensor: Can be embedded in concrete to measure its internal temperature. Changes in temperature cause changes in the length of a tension wire inside the body of the gage. The frequency of vibration of the wire is measured and related to the change in temperature. When a readout unit is connected to the sensor, it sends an electric pulse to coil, which plucks the wire and causes it to vibrate at its natural frequency. A second coil picks up the vibration and returns a frequency to the readout; the frequency reading is converted to units of temperature by applying calibration factors. The measurement of temperature in concrete, soil, and rock includes monitoring temperature rise during the cure of concrete, soil, and rock temperatures adjacent to ground freezing operations and liquid gas storage tanks; interpreting temperature effects on other installed instruments, measuring water temperatures in reservoirs and in boreholes; and measuring air temperature on structure surfaces. Manufacturers include Slope Indicator, Applied Geomechanics, Geokon, and Geo-Instruments.

4. Infrared Temperature Sensors: Non-contact sensors that measure infrared (IR) light radiating from objects in its field of view. Relatively accurate and precise temperature measurements may be obtained remotely. Without calibration to the type of material being observed, a PIR thermometer device can measure changes in IR emission that correspond directly with temperature changes, but the actual temperature values cannot be calculated.

5. Thermal Imaging Cameras: Detect small temperature variations and generate it on a display screen. These cameras have an optic system, detector, amplifier, signal processor, and display. Manufacturers include Extech.

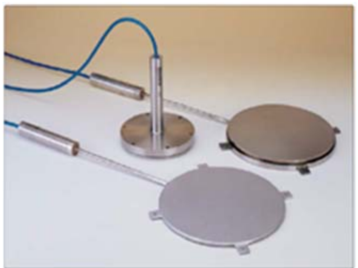
6. Distributed Fiber Optic Temperature Sensor: An optoelectronic device that measures temperatures with optical fibers that function as linear sensors. Temperatures are recorded continuously along the optical sensor cable, and it can monitor distance measurements greater than 30 km. Manufacturers include Applied Geomechanics, Omega, Slope Indicator, Geo-Instruments, Geokon, Raytek, Apogee, Extech, and Omnisens.

<u>Load/Pressure Cells</u>

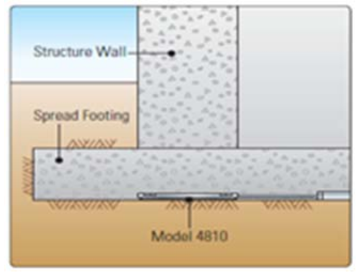
1. Earth Pressure Cells: The two types of earth pressure cells are diaphragm cells and hydraulic cells. Hydraulic earth pressure cells consist of two metal plates welded together around its edges and separated with a small gap that is filled with hydraulic fluid. As earth or other pressures press the plates together, the pressure variation is sent to a readout location. Diaphragm earth pressure cells have a stiff circular membrane attached to a stiff edge ring. The deflection is sensed by an electrical resistance strain gage or vibrating wire transducer. Earth pressure cells are used to measure stress acting on plane surfaces. Applications include monitoring stress in earth embankments, under foundation, retaining walls, and tunnel lining. Figure 3.12 shows a picture of a total earth pressure cell.

2. Tension and/or Compression Load Cells: Use multiple resistance strain gages arranged on a full Wheatstone bridge. The bridge is powered by an external power source and the output is calibrated against load. Compression/tension load cells can be used for applications where the load may go from tension to compression and vice versa. These cells are ideal for space restricted environments. Threaded ends facilitate easy installation. Manufacturers include Geokon, Omega, RST Instruments, LCM Systems, and Futek.

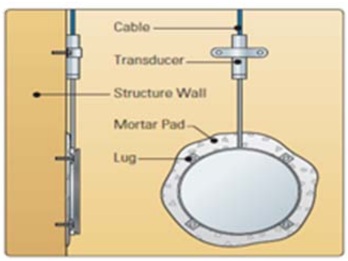
3. Vibrating Wire New Austrian Tunnel Method (NATM) Stress Cells: Designed to monitor stresses on and within lining of tunnels and underground facilities (e.g., in concrete (shotcrete) linings in tunnels). Figure 3.12d shows a picture of the NATM stress sell and method of installation.



(a) Earth Pressure Load Cells (http://www.geokon.com)

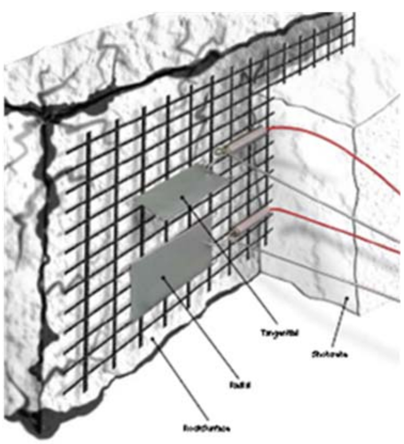


(b) Placement of Earth Pressure Load Cell Under Foundation (http://www.geokon.com)



(c) Earth Pressure Load Cells (http://www.geokon.com)

(d) NATM Stress Cell (http://www.rstinstruments.com)



(e) NATM Stress Cell Method of Installation (http://www.rstinstruments.com)

(f) Picture of Total Earth Pressure Cell (http://www.rstinstruments.com)

Figure 3.12: Earth pressure cells.

Piezometers

Vibrating Wire Piezometers monitor pore water pressure in soils and they can be used to measure water levels. They are sealed in the ground and sense water pressure around itself on a metal diaphragm attached to a vibrating wire. The vibrating wire senses the deflection and reads the frequency change.

1. Vibrating Wire Piezometers monitor pore water pressure in soils. Figure 3.13 depicts pictures of vibrating wire piezometers. Applications of vibrating wire piezometers in monitoring geotechnical structures include: (1) evaluating the performance and stability of embankments; (2) slope stability investigations; (3) pressure monitoring behind retaining walls; and (4) monitoring pore water pressure during fill or excavation.

2. Fully Grouted Multi-point Piezometer String: Monitors pressures behind retaining walls and diaphragm walls, and monitors pore water pressures during fill or excavation. Applications of the system include evaluating the performance of embankments and slope stability. Figure 3.13c shows a Fully Grouted Multi-point Piezometer String and a typical installation plan for this sensor.

Settlement Sensors

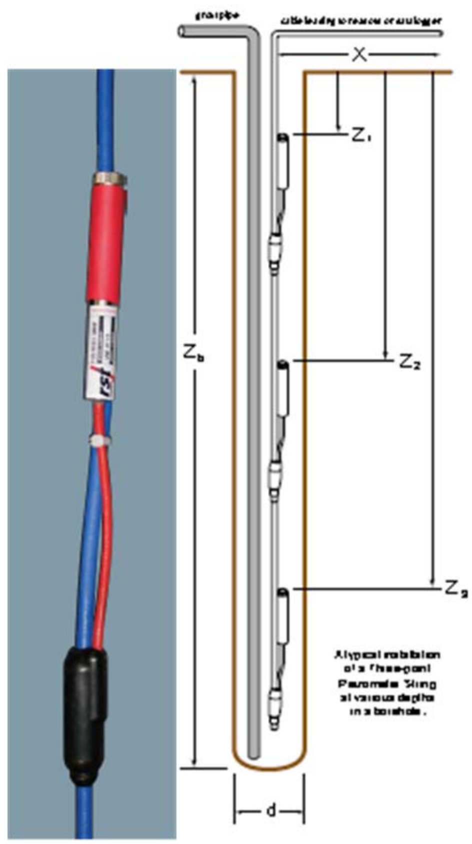
Settlement sensors monitor the settlement and twist of structures, which may be affected by nearby construction activity. The sensors are attached to the bottom of a borehole on stable ground and connected to the ground surface. The amount that the soil settles can be measured by a variety of means such as extensometers and fluid pressures. Figure 3.14 shows pictures of settlement sensors.

1. Vibrating Wire Liquid Settlement System: Monitors settlement or heave in soils and different types of human-made structures such as embankments. The vibrating wire pressure sensor is attached to a settlement plate placed at the location to be monitored. The sensor is attached to two liquid-filled tubes connected to a reservoir in a stable ground. Figure 3.14c shows the Vibrating Wire Liquid Settlement System and typical installation scheme to monitor embankment settlement.

2. Multi Cell Liquid Settlement System: Monitors heave and/or settlement. Applications include structures that are subject to settlement due to nearby construction, tunneling, or natural events. Under settlement or heave, the cell body moves up or down with respect to the level of the fluid within the system. The settlement is measured via LVDT. Datalogger is used to record readings from the settlement cell. Manufacturers of settlement sensors include Geokon, RST, and Slope Indicator. Figure 3.14d shows a settlement cell.

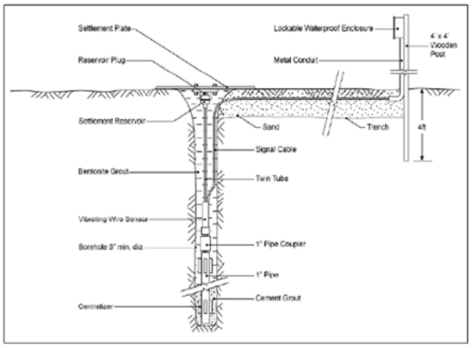
a. Vibrating Wire Piezometers
(http://www.slopeindicator.com)

b. Various Vibrating Wire Piezometers
(http://www.rstinstruments.com)



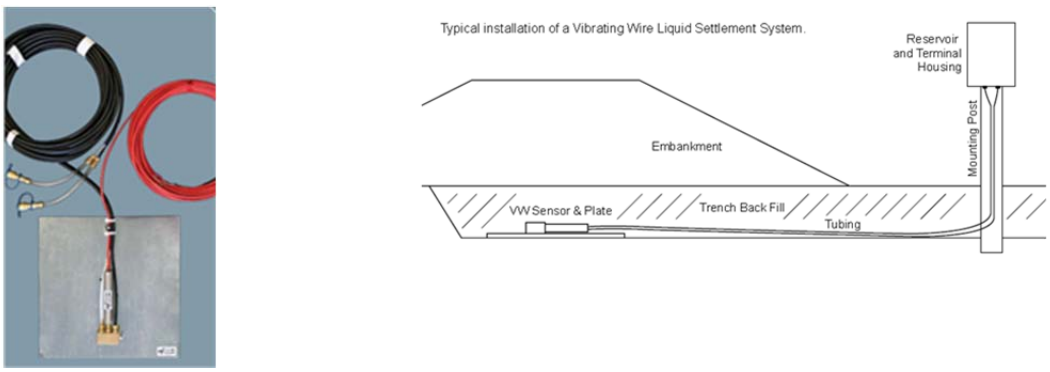
c. Fully Grouted Multi-point Piezometer String and Typical Installation Plan
(http://www.rstinstruments.com)

Figure 3.13: Types of piezometers.



a. Settlement Sensors (http://www.geokon.com)

b. Settlement Sensors installed at a Railroad (http://www.rstinstruments.com)



c. Vibrating Wire Liquid Settlement System and Typical Installation for Monitoring Settlement of Embankment (http://www.rstinstruments.com)

d. Settlement Cell (http://www.rstinstruments.com)

Figure 3.14: Settlement sensors.

Ice Detection Systems

Optical Systems: An ice detector is an optical transducer probe for aviation purposes. The detector has no moving parts, is completely solid, and its principle of operation is entirely optical. Intrusive to the airstream and hermetically sealed, it uses uncollimated light to monitor the opacity and optical refractive index of the substance on the probe. It is desensitized to ignore a film of water.

The Goodrich Ice Detector measures precipitation transitions between liquid and solid states. The sensor is designed to measure the intensity and duration of ice storms and differentiates rain from freezing rain as temperatures approach freezing. Ice accumulations, as low as 0.005 inches (0.13 mm), can be detected. Manufacturers of ice detectors include Capmbell Scientific. Figure 3.15 shows an ice detector.

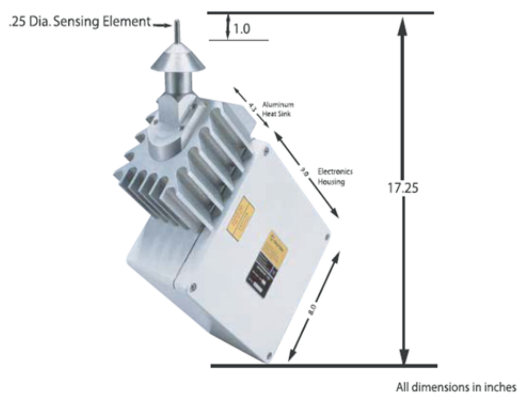


Figure 3.15: Ice detector (http://www.campbellsci.ca).

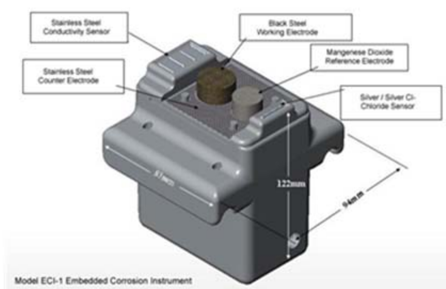
Corrosion Detection

The corrosion of steel within a structure can be monitored by several types of sensors. As steel corrodes, there is a decrease in the cross-sectional area of the steel, which weakens structures. The corrosion rate can be measured to prevent failure and for durability design. Figure 3.16 shows pictures of corrosion sensors.

1. Embedded Corrosion Instrument (ECI): An electronic corrosion sensor that provides real-time monitoring of reinforcement steel in concrete structures. The ECI is designed to monitor bridges, buildings, dams, erosion control structures, flood control channels, parking garages, piers, pylons, roadways, and spillways. The ECI monitors the following factors in corrosion: (1) linear polarization resistance; (2) open-circuit potential; (3) resistivity; (4) chloride ion concentration; and (5) temperature. ECI monitors the corrosive environment in steel-reinforced concrete during:

i. Construction: monitoring chloride concentration, temperature, and resistivity will help identify construction errors at an early stage.
ii. Curing of concrete: monitoring temperature and moisture content will help determine if the required strength of the concrete is achieved.
iii. Long-term basis during use of the structure: monitoring linear polarization resistance, open-circuit potential, resistivity, chloride ion concentration, and temperature.

2. Concrete Corrosion Sensors: Measure corrosion initiation and corrosion rate in reinforced concrete structures. Measurements are performed at four different depths between the concrete surface and the reinforcement bars depth.
3. Linear Polarization Resistance: This approach estimates the rate of corrosion of steel bars in concrete and monitors corrosion rates directly and in real time.
4. Electrical Impedance
5. Ultrasonic C-Scan: Detect voids in grout and corrosion in post-tensioning tendons.



a. The Embedded Corrosion Instrument – ECI (Virginia Technologies, Inc.)

b. Installation of ECI corrosion meter (Virginia Technologies, Inc.).

c. Concrete Corrosion Sensor (http://www.esands.com)

d. Linear Polarization Resistance (http://www.ndt.net)

Figure 3.16: Corrosion sensors.

Scour Monitoring/Measurement Devices

Scour is the erosion of waterway soils and sediments that can undermine bridge foundations, and is interpreted as a change in the distance from the river bottom. Scour monitoring systems collect real-time data to ensure the integrity of the bridge foundation. The system uses Sonar Altimeters that continuously measure the amount time for a sound wave to travel from the transducer to the river bottom and back. Figure 3.17 shows a scour monitoring system and a Sonar Altimeter.

1. Magnetic Sliding Collar: This device has a steel pipe driven into the channel bottom with a collar around it. The location of the collar is detected by the magnetic field created by magnets in the collar.

2. Float Out Device: Has a radio transmitter buried in the channel bed at a predetermined depth. When scour causes the channel bed to reach the device, it floats and emits a radio signal that is detected nearby.

3. Sonar Scour Device: A relatively low-cost device that consists of a sonar device connected to a data logger that tells the sonar when to collect data. It also determines the depth to the bottom of the river.

4.

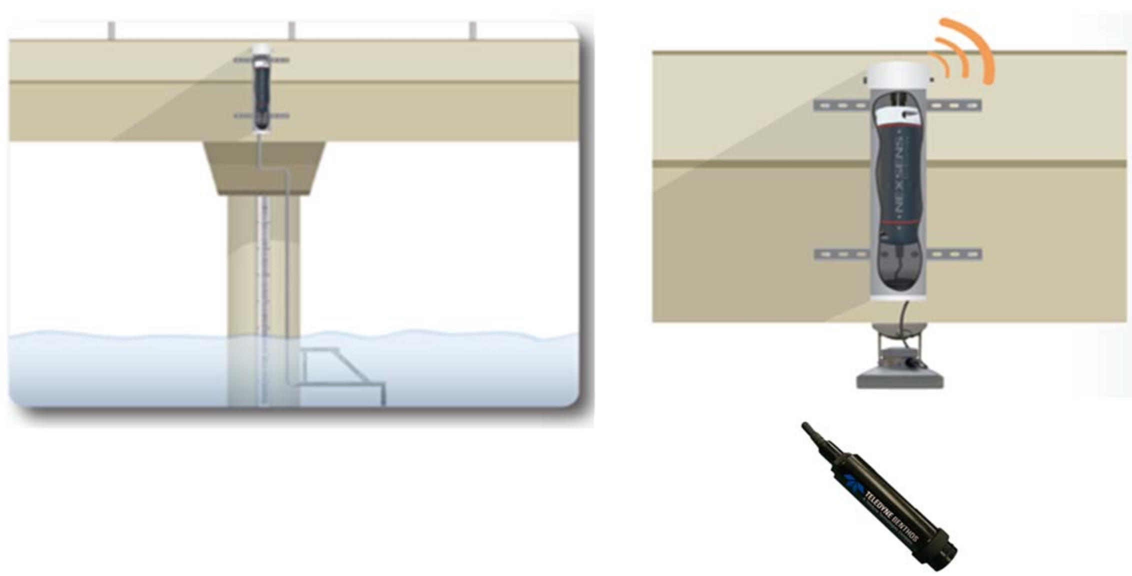


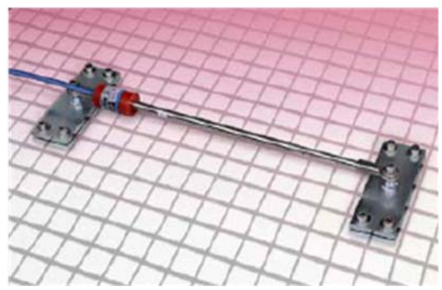
Figure 3.17: Scour monitoring system and sonar altimeter (http://nexsens.com).

Crack Detection

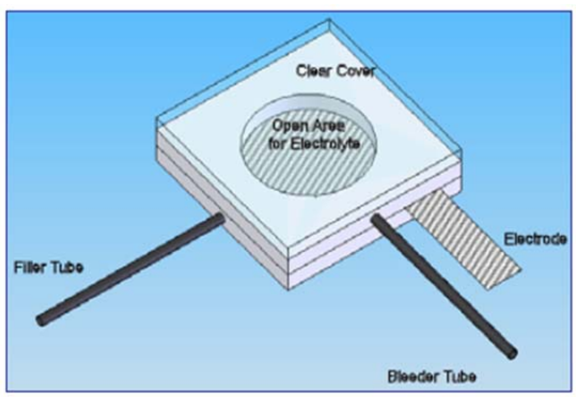
1. Electrochemical Fatigue Sensing: According to its manufacturer, "the Electrochemical Fatigue Sensor is a nondestructive fatigue crack inspection method used to indicate if fatigue cracks are actively growing. During an EFS inspection, a sensor is applied to each location of interest. Crack activity detection occurs for areas under the sensor."

2. Vibrating Wire Crackmeters: Measure movement across surface cracks and joints. Applications include monitoring tension cracks in soils and joints in rocks. Figure 3.18 shows selected crack detection sensors.

a. Vibrating Wire Crackmeter (http://www.geokon.com)



b. Vibrating Wire CrackmeterConfigured with Geogrid (http://www.geokon.com)



c. Electrochemical Fatigue Sensor (http://www.fra.dot.gov)

Figure 3.18: Crack detection sensors

Tunnel Profile Monitoring System

The Tunnel Profile Monitoring System monitors tunnel deformation and it consists of series of linked rods attached to the tunnel wall. Applications include monitoring ground opening during construction for safety and control, monitoring tunnel deformation due to nearby construction, and long-term monitoring of the deformation and performance of existing tunnels. Figure 3.19 depicts a tunnel profile monitoring system.

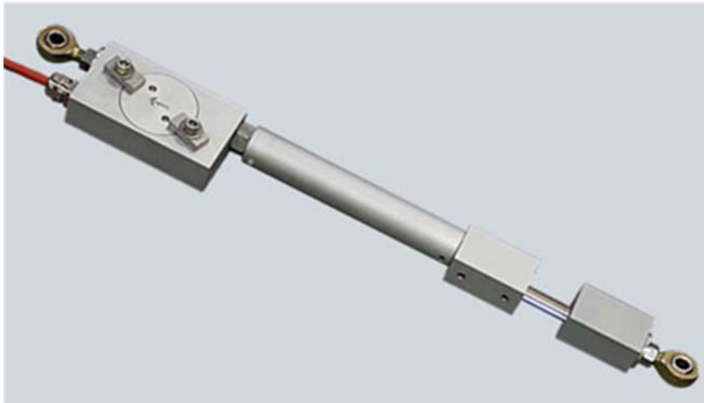


Figure 3.19: Tunnel profile monitoring system (http://www.rstinstruments.com).

Weigh-in-Motion Systems

Weigh-In-Motion (WIM) devices are designed to capture and record truck axle weights, axle spacing, and gross vehicle weights as they drive over a sensor. Unlike road surface, current WIM systems collect data on moving trucks without the need for them to stop. Gross vehicle and axle weight monitoring is useful in: (1) pavement design, monitoring, and research; (2) bridge design, monitoring, and research; (3) size and weight enforcement; (4) legislation and regulation; and (5) administration and planning. Figure 3.20 shows a WIM station.

Figure 3.20: Weigh-in-motion systems
(http://www.oregon.gov)

Weather Stations

Weather Stations are devices used for meteorological and climatological monitoring. They typically measure temperature, wind speed, wind direction, precipitation, and solar radiation. A weather station is depicted in Figure 3.21.

Figure 3.21: Weather station
(http://www.campbellsci.com)

Multi-Depth Deflectometers

Multi-Depth Deflectometers measure deflection and/or permanent deformations in the various pavement layers. Figure 3.22 shows a multi-depth deflectometer.

Figure 3.22: Multi-depth deflectometer
(http://www.dynatest.com)

3.3 Data Acquisition and Processing

Simple SHM systems may use a portable or hand-held indicator or datalogger to collect and store the data from sensor(s). Such an approach is used for a SHM with a small number of sensors or for a system that only requires a measurement at infrequent intervals (Phares et al., 2005). Advanced systems incorporate a global SHM system with a large number of digital sensors (to avoid A/D conversion) so data can be surveyed, collected by the data acquisition system and processed at predetermined time intervals.

Among others, the data acquisition system, developed by Campbell Scientific, has been used in number of SHM projects. This system is compatible with most commercially available sensors, thereby providing a reliable platform for structure/bridge monitoring (Phares et al., 2005).

A comprehensive SHM uses a large number of different sensors and corresponding networks, which results in a very complex electronic system. For example, the SHM system for the Parkview Bridge provides continuous monitoring of the bridge deck to assess the effects from environmental factors such as temperature and from traffic loads, evaluate its deterioration rate, initiate maintenance and repairs when needed, and predict the remaining service life (Abudayyeh et al., 2010).The SHM deployed for the Parkview Bridge is composed of 184 vibrating-wire strain sensors (VWSG) with built-in thermocouples (thermistors) installed in the bridge deck panels. In order to process/analyze the data, the developed system includes 12 multiplexers, 2 data loggers, 2 modems, a remote computer workstation in a laboratory, and the necessary wiring for communication and data transfer, Figure 3.23 (Abudayyeh et al., 2010).

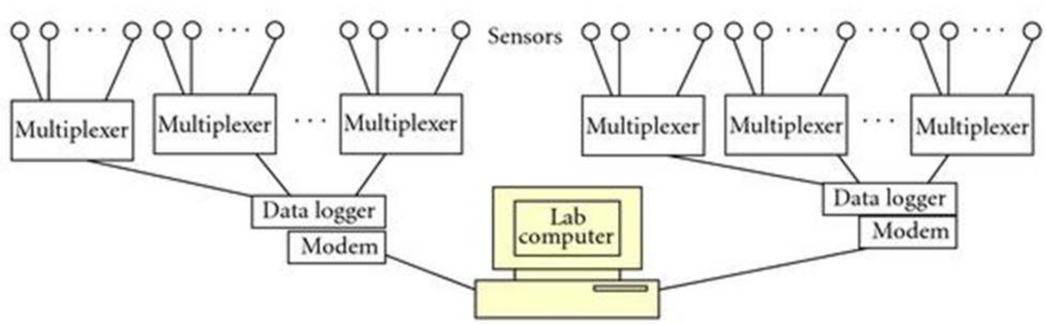
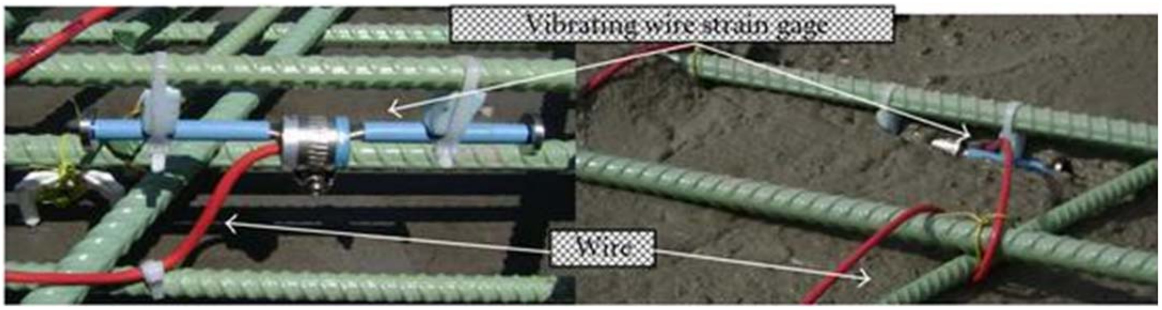


Figure 3.23: Schematic view of the SHM system configuration used for Parkview Bridge (Abudayyeh et al., 2010)

Often sensors are located away from the data acquisition system and/or the monitoring unit so that reliable data transmission is realized via wire/wireless link, which is an essential component of comprehensive SHM systems (Figure 3.24).



(a) Properly secured sensor

(b) Conduit placement

(c) Exposed Conduit, Wire, and Splicing.

(d) Cabinets and data logging equipment.

Figure 3.24: The components and wiring of the sensor network (Abudayyeh et al., 2010)

The majority of conventional data collection systems rely on wire-connected instrumentation where sensors are placed at critical points along a structure and connected to a central data acquisition system with cables of various types using Ethernet local area network, LAN (Phares et al., 2005, Abudayyeh et al., 2010). Due to reliability issues and high installation and maintenance costs, state-of-the-art SHM employ the wireless technology instead of the wire connection, Figure 3.25 (Akyildiz, 2002).

For example, Advanced Telemetrics International (ATI) developed a Wireless Bridge Health Monitoring Telemetry System, Figure 3.26 (ATItelemetry.com 2011), which can transmit the sensor signal up to within a four-mile line of site, thereby eliminating long cable runs. The telemetry transmitter is housed in a weatherproof enclosure for outdoor use and it supplies excitation to the sensor. Operating from internal rechargeable batteries or an external DC power source, data can be transferred over a 2.4 GHz spread spectrum band up to 300 updates/channel/second for up to 32 channels.

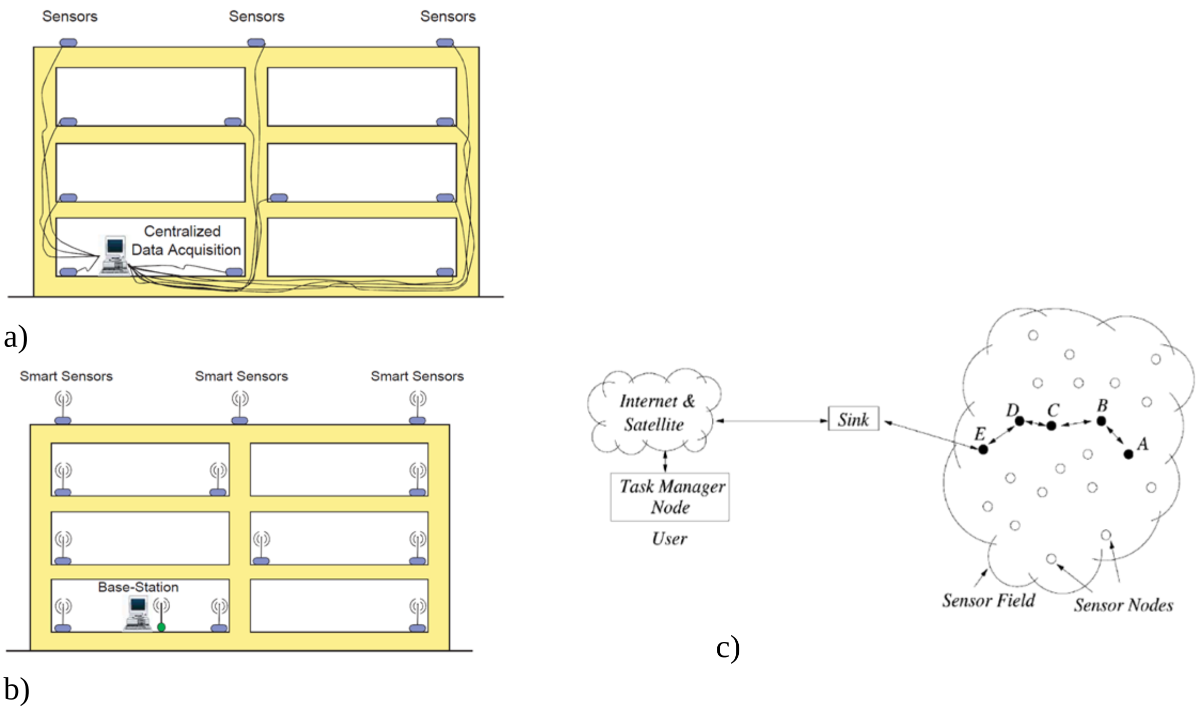


Figure 3.25:(a) Traditional SHM system using centralized data acquisition (b) wireless SHM system using smart sensors (Spencer et al. 2004) and (c) the topology of the sensor nodes scattered in a wireless sensor field (Akyildiz, 2002).

Figure 3.26: Implementation of a Wireless Bridge Health Monitoring Telemetry System (ATItelemetry.com 2011).

The wireless SHM can be effectively used to survey the data from modern sensors based on “Smart Dust,” “Smart Aggregate,” “Smart Pebble” concepts (Pister, Phares et al., 2005; Watter et al., 2003). Such stay-alone and self-powered sensors eliminate the need for external power, thereby decreasing the sensor size, improving the life span, and/or eliminating the need for cabling. These smart wireless sensors are embedded in a bridge deck during the construction (retrofit) or in the cored and installed in patched holes (Figures 3.27 and 3.28).

“Smart Pebble” is a new 1.5-in. diameter wireless sensor of chloride levels in concrete developed by SRI International for Caltran applications, Figures 3.27 to 3.29 (Watter et al., 2003). The device contains a 125-kHz antenna (for communication with reader), an RFID (radio-frequency identification) device that provides a unique identifying code, and temperature compensated electronic circuitry that interfaces with a potentiometric chloride sensor (Figure 3.29).

The “Smart Aggregate” Wireless Embedded Sensor Platform, WESP-SA (U.S. patent 6796187) was developed in the Johns Hopkins University for long-term environmental / corrosion monitoring in bridge decks (Figures 3.28 to 3.30). The WESP-SA is designed to meet the following requirements (Srinivasan et al., 2004; Carkhuff and Cain, 2003):

- Wireless system for power and communications
- Small size, in the order of concrete aggregates
- Strong and mechanically robust
- Long service life
- Low manufacturing and use cost

It was demonstrated that the smart aggregate can survey the environmental data about conditions within the bridge deck (Srinivasan et al., 2004; Carkhuff and Cain, 2003). Different types of WESP-SA were developed for measuring the concentration of chloride ions, the corrosion rate (using a sacrificial electrode) and for measuring pH of concrete (Phares et al., 2005; Carkhuff and Cain, 2003). These sensors were applied for SHM of a bridge deck in Montgomery County, Maryland (Phares et al., 2005; Carkhuff and Cain, 2003).

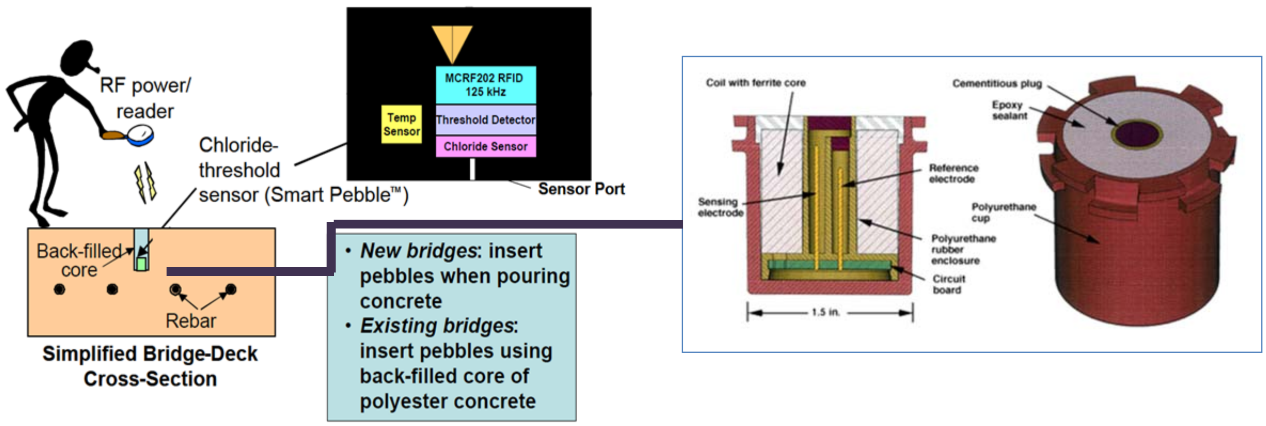


Figure 3.27: The design and application of Smart Pebble sensor (Watters, 2003).

Figure 3.28: Installation of Smart Aggregate units (Carkhuff, 2003)

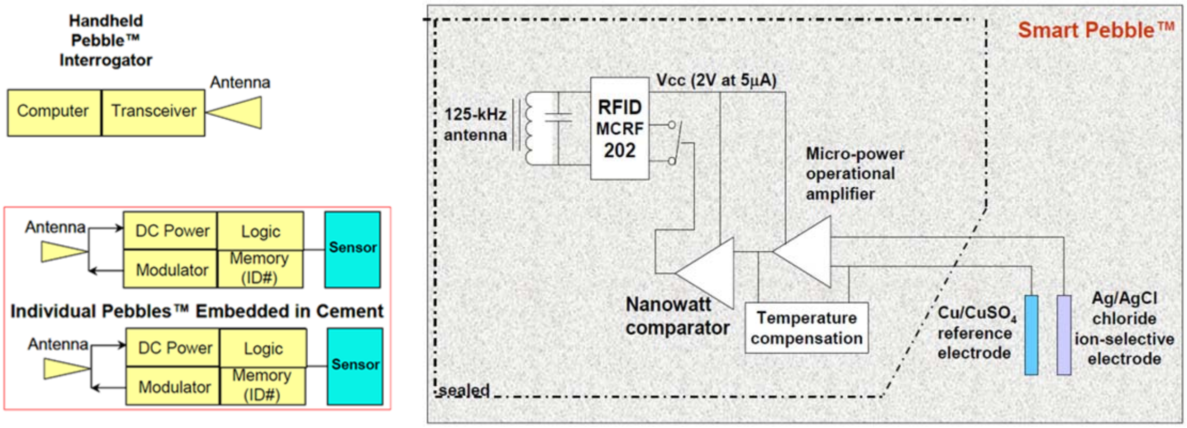


Figure 3.29: The concept (left) and detailed diagram (right) of Smart Pebble sensor (Watters, 2003).

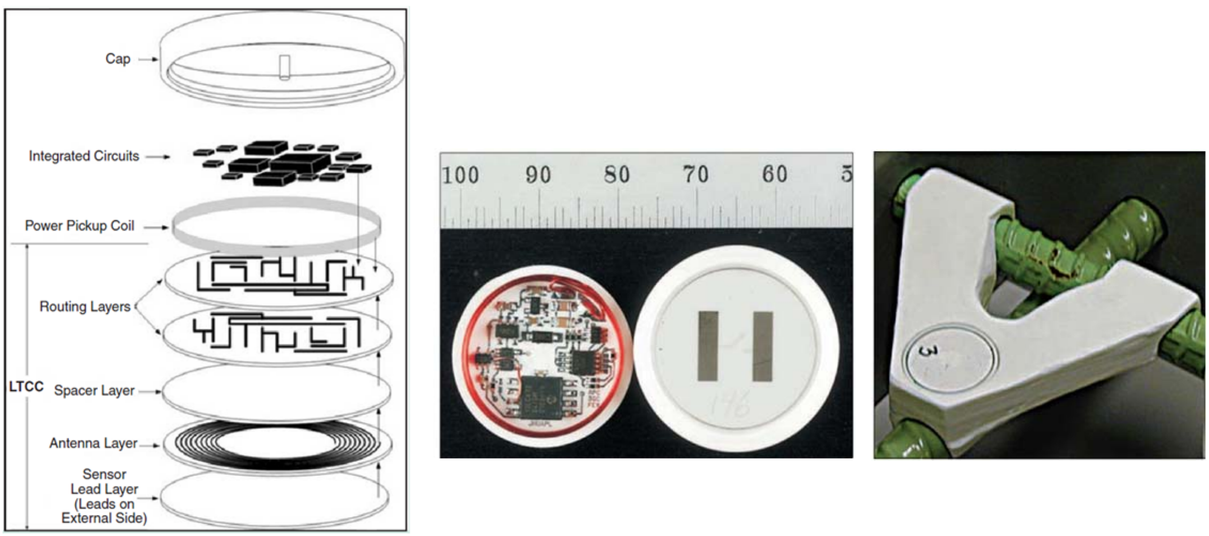


Figure 3.30: Design and assembling of Smart Aggregate WESP-SA unit (Carkhuff, 2003).

The University of Sheffield instrumented the Tamar Bridge in Plymouth, UK, with SHM systems to evaluate its dynamic/quasi-static behavior and environmental conditions (sine.ni.com, 2011). The National Instruments Wireless Sensor Network (WSN) platform with a WSN-3202 measurement node was used to digitize the analogue inputs from the sensors and transmit them wirelessly using IEEE 802.15.4 radio over the 2.4 GHz frequency band. The sensor data were sent using intermediate WSN-3202 router node to a WSN-9791 gateway node connected to the PC via Ethernet. The NI LabVIEW software was used to acquire and store the received data on the PC (sine.ni.com, 2011).

A SHM system was designed for acquiring, storing, classifying, and displaying earthquake sensor data (Wong et al., 2005).The reported SHM had data acquisition system with wireless sensors based on the MICA2 platform with MEMS accelerometers manufactured by Crossbow Technology. The sensors are equipped with an onboard microprocessor running the TinyOS operating system and use a self-organizing ad-hoc network to communicate data to the host station via a Chipcon CC1000 radio transceiver operating on a frequency of 916 MHz, 433 MHz, or 315 MHz and a maximum data rate of 38400 bits/sec. The host station is connected to a computer via an RS-232 serial port which enables TinyOS commands to be sent to the MICA2 sensors (Wong et al., 2005). In this system, a single MICA host station, computer, and the MICA2 sensor boards were used as the hardware components for the wireless data acquisition system, Figure 3.31 (Wong et al., 2005).

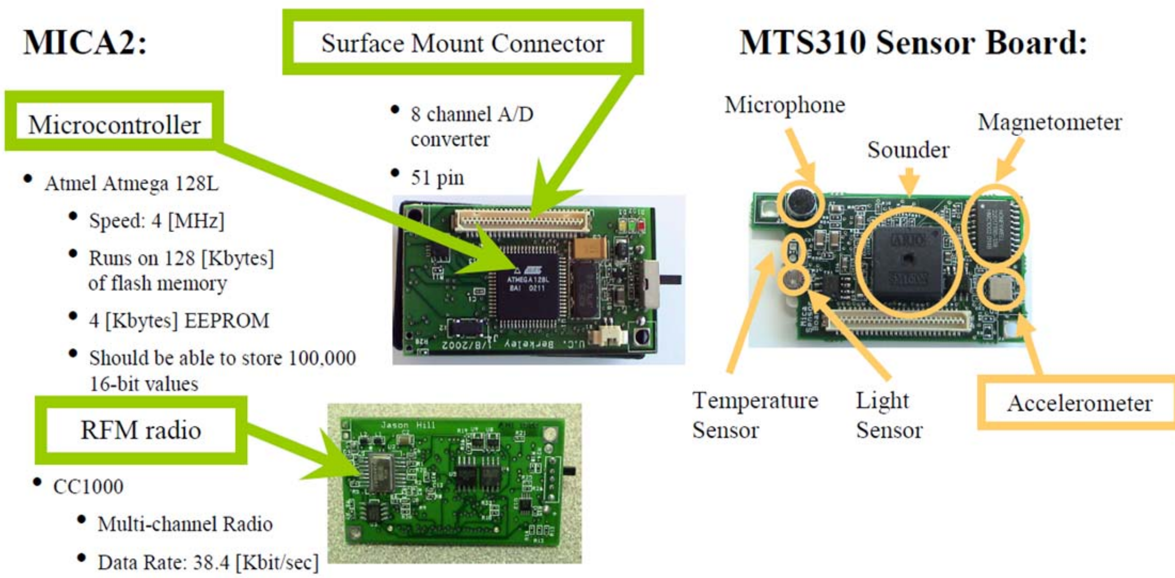


Figure 3.31: MICA2 components and MTS310 wireless sensor board (Wong et al., 2005).

The sensor responses were ingested into the metadata repository using the NEES grid metadata service (NMDS) as the backend storage system. The information on sensor nodes including their location within the structure, characteristic properties, their responses and results of the structural performance assessment are visualized using Web pages, convenient for easy access, browsing and searching the data, Figure 3.32 (Wong et al., 2005).

Figure 3.32: Monitoring web interface using MICA2 (Wong et al., 2005).

Web interface is an attractive media for representation of sensor data specific to the sensors location using geo-based web interfaces like Google Maps (Santini, 2008).

Different platforms can be used to deposit and represent the data from sensor networks such as:

- IrisNet (Internet-scale Resource-Intensive Sensor Network Services)
- SensorBase.org, which offers a centralized data storage and management system
- Global Sensor Networks Project (GSN), which facilitate the programming and deployment of sensor networks
- SenseWeb
- Desthino (Distributed Embedded Things Online) (Santini, 2008)

GSN is an extendible software infrastructure for rapid deployment and integration of heterogeneous wireless sensor networks. It is already tested with Mica2, Mica2Dot, TinyNodes, Wisenode, wired and wireless cameras, RFID readers. GSN is used for streaming data at the ETH Center for Competence Environment and Sustainability (CCES) and integrates sensors of a variety of types, from groundwater monitoring, to plant ecology, cryospherics and meteorology.

Similar to blogging, SensorBase.org allows to "slog" sensor network data (e.g., temperature, humidity). Slogging allows third-party application programmers to retrieve data easily and efficiently and can be used as an interface for 3D/spatial mapping, and/or tracking sensor data with Google Earth, ArcGIS or ArcMap, Figure 3.33.

SenseWeb is a platform developed by Microsoft, which develops sensing applications that use the shared sensing resources and our sensor querying and tasking mechanisms. SensorMap is one such application that mashes up sensor data from SenseWeb on a map interface and provides interactive tools to selectively query sensors and visualize data, along with authenticated access to manage sensors (http://research.microsoft.com/en-us/projects/senseweb/).

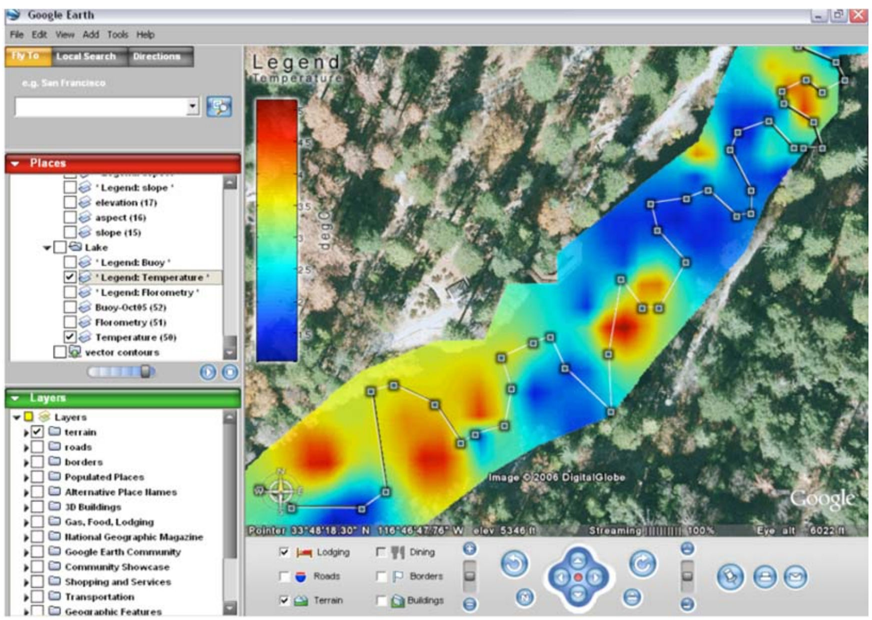


Figure 3.33: SensorBase.org can be used for mapping of sensor data with Google Earth (http://sensorbase.org/)

Chapter 4

Case Studies in Infrastructure Health Monitoring

A comprehensive review on sensor-based SHM applications in bridges was reported by Abudayyeh et al. (2010); the characteristics of sensor networks from this study are summarized in Table 4.1.

Table 4.1:Summary of the health monitoring case study (Abudayyeh et al. 2010)

Case study	Types of sensors used*	#of sensors used	Sensor placement	Data collection time intervals	Load type monitored
Confederation bridge (Canada)	(1),(2),(3),(4), (5),(6),(7), (8)	389	Deck, Beam, Pier	Variable	Static/dynamic
Pemiscot county bridge, Missouri (U.S.)	(1), (3), (4)	64	Deck, Beam	–	Static
North halawa valley viaduct, Hawaii (U.S.)	(1), (4)	200	Deck, Beam	5 minutes/2 hours	Static
Parkview bridge, Michigan (U.S.)	(1), (4)	184	Deck	10 minutes	Static

*Note: sensor types: (1) Vibrating wire strain gage, (2) Fiber optical, (3) Resistance strain gage, (4) Thermocouples, (5) Accelerometer, (6) Tilt-meter, (7) Displacement, and (8) Ice-force.

4.1 SHM System for Bridges – Connecticut

Structural health monitoring systems were developed and implemented (DeWolf, 2006) for different types of bridges in Connecticut through research collaboration between the Connecticut Department of Transportation and the University of Connecticut. One of the objectives was to collect data on the long- and short-term performance of these bridges. The research effort included investigating, developing, and evaluating methods for long-term measurements and monitoring of the structural behavior of bridges. The short-term SHM of the bridges consisted of strain measurements, while long-term monitoring involved vibration measurements using accelerometers.

DeWolf et al. (2006) described the development of a generic specification for the bridge health monitoring systems in Connecticut. Sensors consisted of accelerometers, strain gages, temperature transducers, and tilt-meters. Table 4.2 summarizes the SHM systems deployed for different types of bridges in Connecticut. Data were collected on a continuous basis; all data sets were taken under normal traffic loading. Data collection included temperature and tilt on specific time intervals; strain and accelerations were collected on a trigger basis (data were saved only when a larger vehicle had crossed the bridge).

Short-term SHM was achieved using portable systems for determining strains and stresses. An average of eight strain gages were used from one to three days. Short-term monitoring was carried out on 20 different steel bridge types and two reinforced concrete bridges. The following monitoring parameters were evaluated based on the short-term data/information collected:

1. Characterization of fatigue problems in terms of causes, extent, severity, and the need to take action (repair, maintenance). Fatigue problems were monitored at diaphragm connections, connections between girders, weld crack problems, and cracks at beam cross-sections changes.
2. Evaluation of structural capacity of major members with consideration of aging and corrosion.
3. Excessive deflection of newly constructed curved bridges.

Long-term vibration monitoring was used to develop and design a prototype monitoring system for long-term installation on bridges.

Table 4.2: Four Fully-Operational Bridge Monitoring Systems in Connecticut (DeWolf 2006)

Bridge	**Bridge Description**	**Monitoring System**	**Date of Installation**
Post-tensioned Box Girder Bridge	Curved, post-tensioned five-celled box girder bridge continuous over three unequal spans	6 accelerometers 16 strain gages 12 temperature sensors 6 tilt-meters	1999
Post-tensioned Segmental Box Girder Bridge	Multi-span segmental box-girder bridge with post-tensioning	16 temperature sensors	1999
Steel Box Girder Bridge	Multi-span curved continuous double steel box-girder bridge	8 temperature sensors 6 tilt-meters 8 accelerometers	2001
Steel Multi-Girder Bridge	Three-span, simply Supported bridge with eight steel plate girders	20 strain gages	2004

The SHM systems developed for the Connecticut DOT included the following components:

1. System Control Unit: hardware and computer for monitoring and data analysis
2. Sensors: collecting data
3. Software: system control, system and sensor operation, data analysis, and communication
4. Communication System: data transfer from monitoring location

DeWolf et al. (2006) described the installation and operation of the bridge health monitoring systems on Connecticut bridges as follows:

1. Identifying locations for the cabinets that house the control system, communication system, and cooling/heating unit.
2. Installing wires to provide electricity and phone/DSL access to the cabinets.
3. Installing the various types of sensors
4. Data collection
5. Data storage

Figure 4.1 shows sensors locations for a post-tensioned box girder bridge. Four types of sensors were used for bridge monitoring, which consisted of 6 accelerometers, 16 strain gages, 12 temperature sensors and 6tilt-meters. All sensors were placed on the inside of the box girders, distributed over the three spans and across the cross-section, as shown in Figure 4.1 (DeWolf 2006). Figure 4.2 shows pictures of installation of bridge health monitoring components for a post-tensioned box girder bridge in Connecticut.

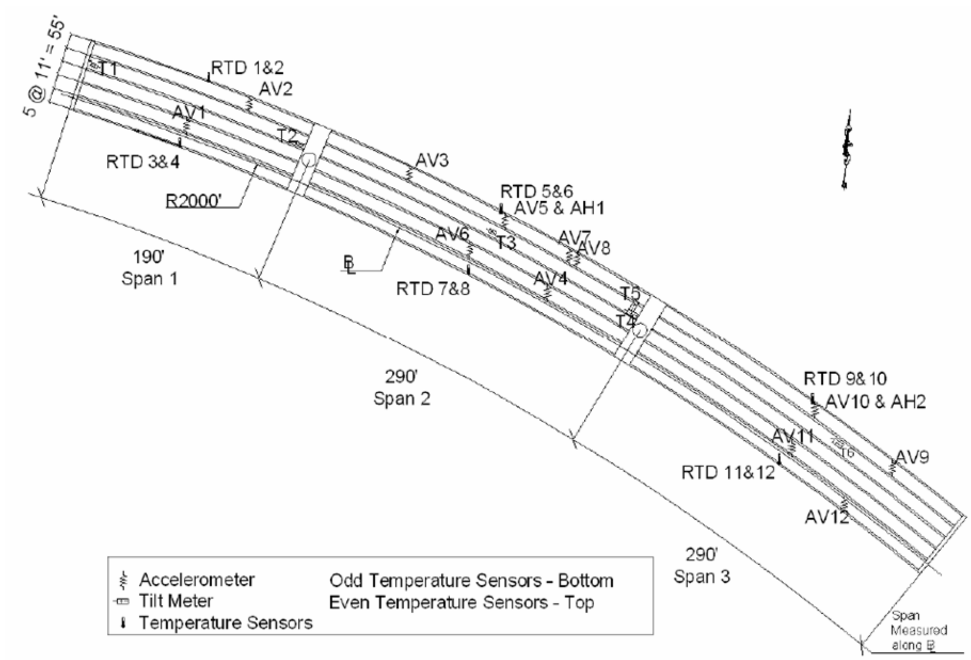


Figure 4.1: Sensors locations for post-tensioned box girder bridge (DeWolf et al. 2006)

(a) Installation of temperature sensor (b) Enclosure for system control and cable conduit

Figure 4.2: Installation of bridge health monitoring system for post-tensioned box girder bridge in Connecticut (DeWolf et al. 2006)

DeWolf et al. (2006) presented a detailed installation plan for a steel box girder bridge that was part of the interchange between I-94 and I-91 in Hartford, Connecticut. The bridge health monitoring system consisted of 8 temperature sensors, 6 tilt-meters and 8 accelerometers located in the outer box section, as shown in Figure 4.3.

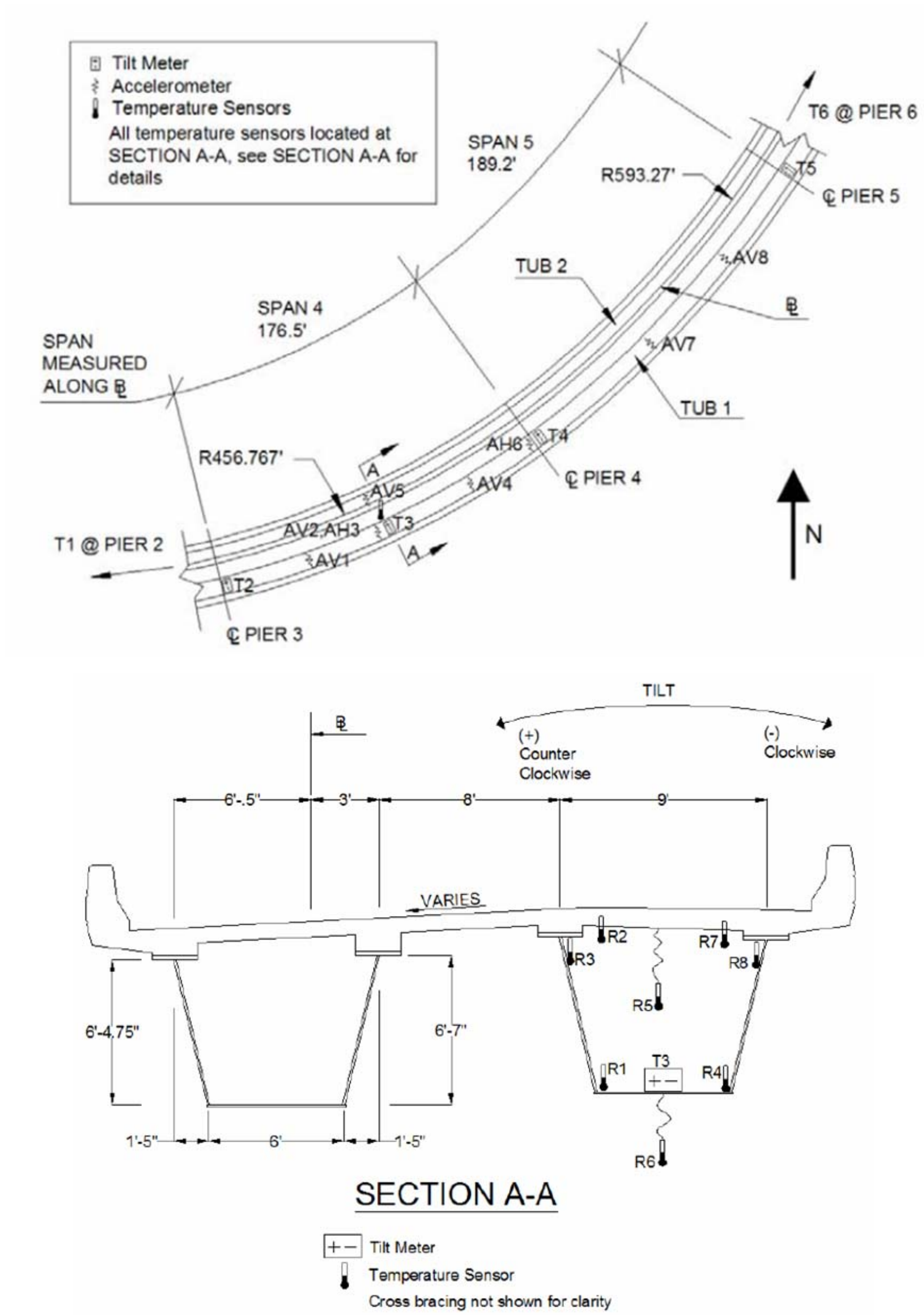


Figure 4.3: Instrumentation plan for steel box girder bridge in Connecticut (DeWolf et al. 2006)

Based on research and implementation of the bridge health monitoring systems described, DeWolf et al. (2006) concluded that the long-term research project provided: (1) information on how bridge monitoring systems can be used in the evaluation of the in-service behavior; (2) information that can be used for the long-term structural health monitoring of each bridge;

(3) information that will assist the Connecticut DOT in managing the State's bridge infrastructure.

4.2 Bridge Monitoring TestBed – San Diego

Fraser (2006) developed and verified a bridge health monitoring "Testbed" by instrumenting bridge-deck panels for a bridge located on the University of California-San Diego campus. The system has the capability to handle and process sensor data and video signals. One of the objectives was to develop a correlation between acceleration from traffic-induced vibration and moving traffic loads. Figure 4.4 shows the integrated research framework based on the Testbed. Fraser et al. (2010) deployed the bridge health monitoring system on a reinforced concrete box girder bridge on Volt Drive/I-5, as shown in Figure 4.5. The monitoring system consisted of an accelerometer array of 20 sensors installed at 15-ft spacing to measure vibration in the vertical direction and integrated video camera monitoring framework. Details of the health monitoring system are depicted in Figure 4.6.

Sensor data were collected via a synchronized data acquisition system housed in the instrumented bridge deck. Wireless Internet technology was used for data transmittal and streaming from the bridge site to a Web-based database; data archiving and a Web portal for data access was also created. Figure 4.7 shows image-sensor data correlation as a vehicle passes by the sensor.

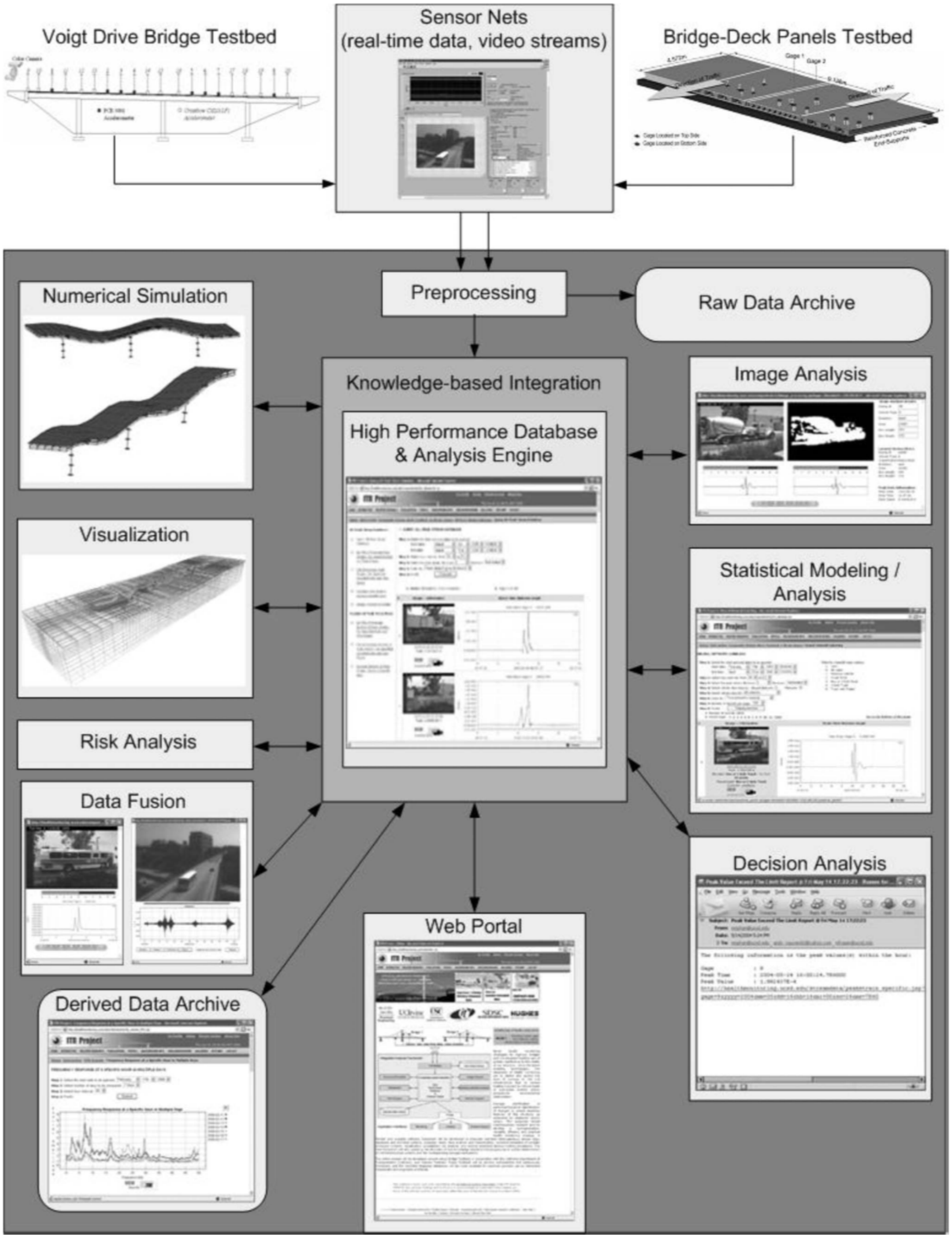


Figure 4.4: Integrated research framework based on project Testbeds (Fraser et al. 2010)

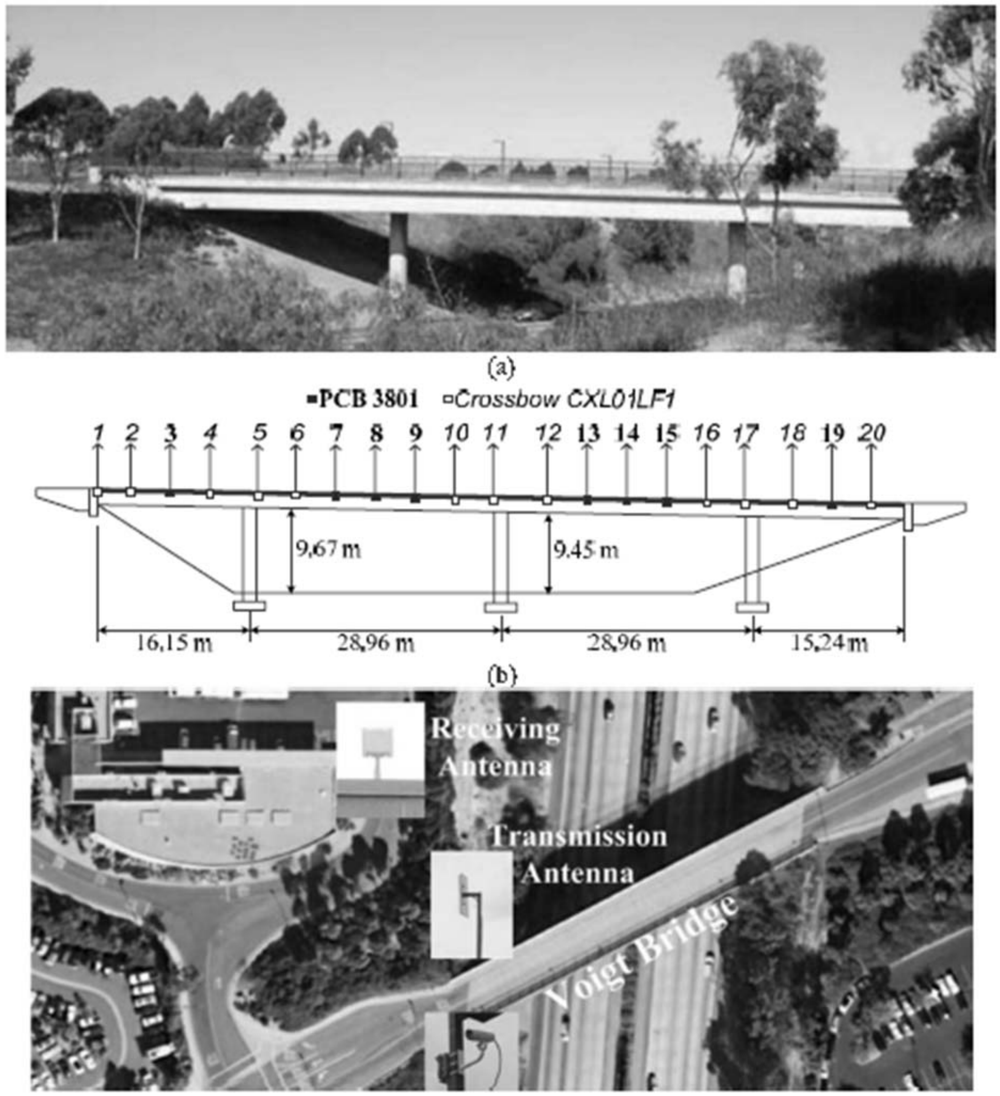


Figure 4.5: (a) Voigt Drive/I-5 Bridge Testbed; (b) elevation view of Testbed with locations of accelerometers; (c) locations of camera and wireless transmission antennas deployed on monitoring system (Fraser et al. 2010)

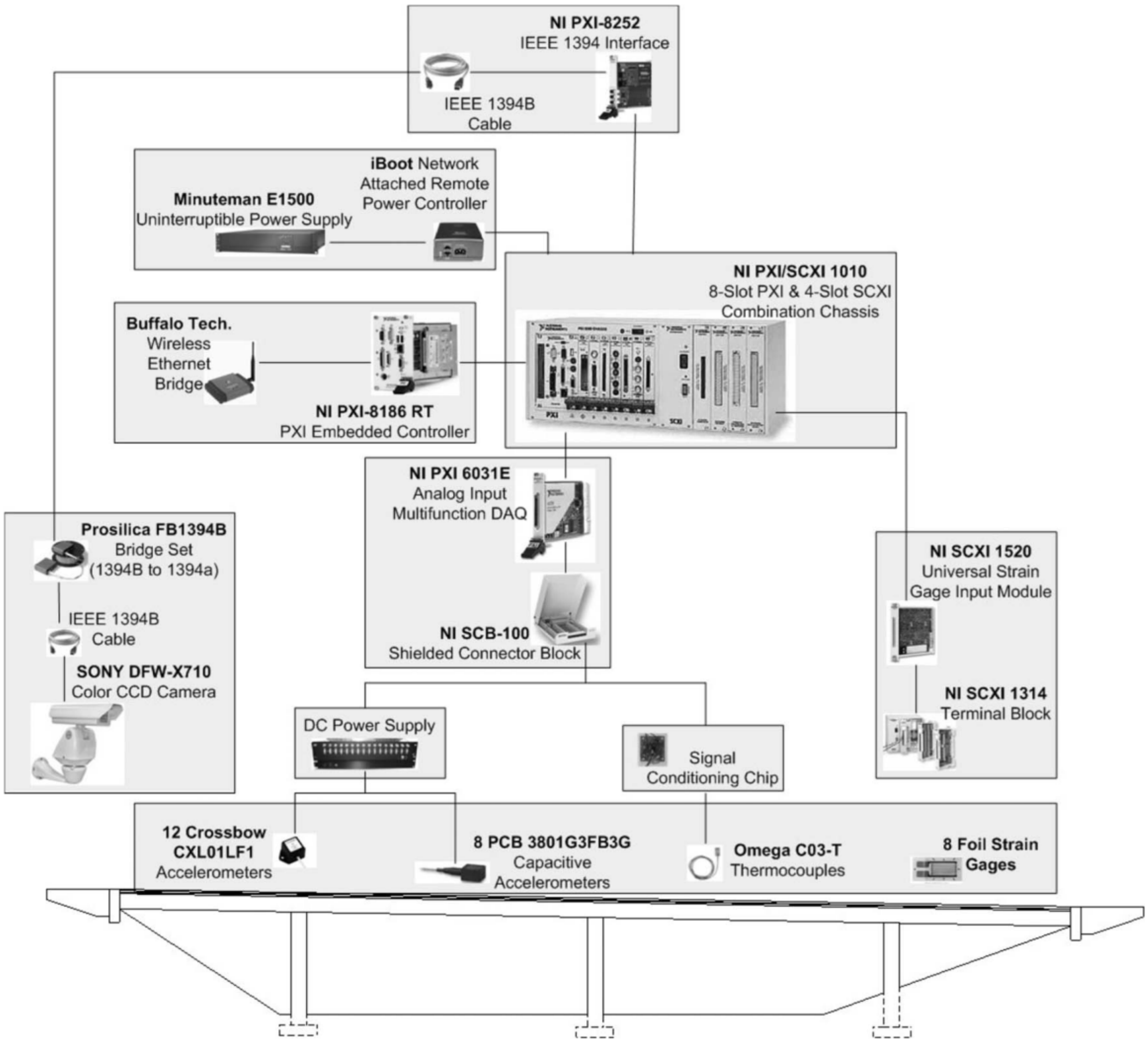


Figure 4.6: Schematic of hardware architecture (Fraser et al. 2010)

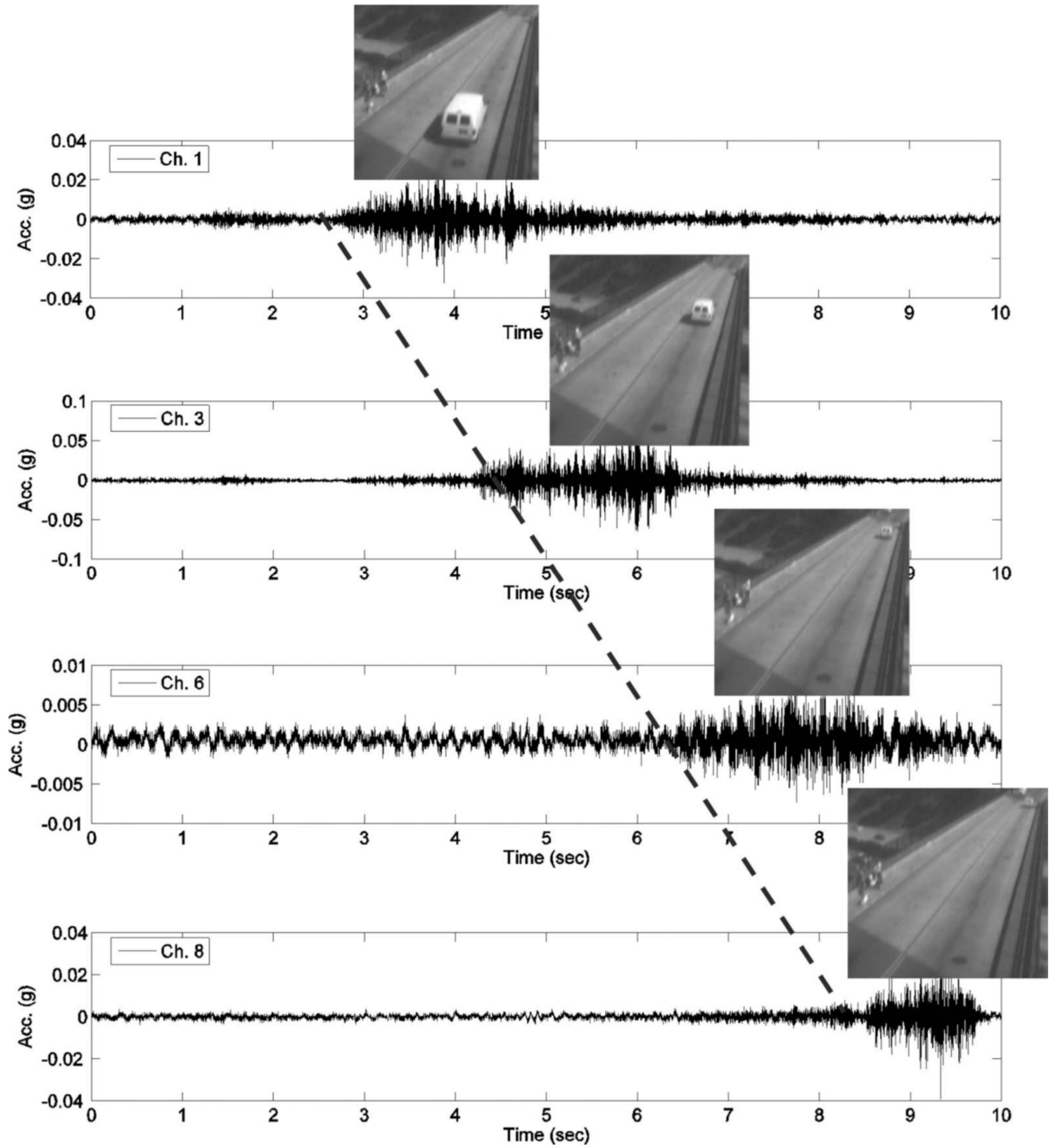


Figure4.7: Schematic display of time-synchronized acceleration and video vertical response at the middle of each span; Sensors 3, 8, 14, and 19 of Figure 2.38 (Fraser et al. 2010)

4.3 SHM of Pier Foundation on I-10 Twin Span Bridge, Louisiana

An SHM system was installed on one of the piers of the I-10 Twin Span Bridge over Lake Pontchartrain in Louisiana. The bridge was constructed to replace the damaged bridge during a storm surge in 2005 from Hurricane Katrina. The objectives of the monitoring system were to verify the design, perform short-term monitoring of the foundation behavior during lateral pile load test, and conduct long-term monitoring of the bridge/foundation during certain events such as wave, wind, and vessel impact forces.

The instrumentation plan was carried out on the M19 eastbound bridge pier, which is supported by a group of battered square precast pre-stressed concrete piles. Each pile is 110 ft. long with a 36″×36″ square cross-section and a circular void of 22.5″ in diameter. SHM sensors installed on selected piles and pile caps included strain gages, accelerometers, tilt-meters, water pressure cells, and corrosion meters. Details of the instrumentation plan on the bridge pier are shown in Figure 4.8 (Abu-Farsakh et al. 2010).

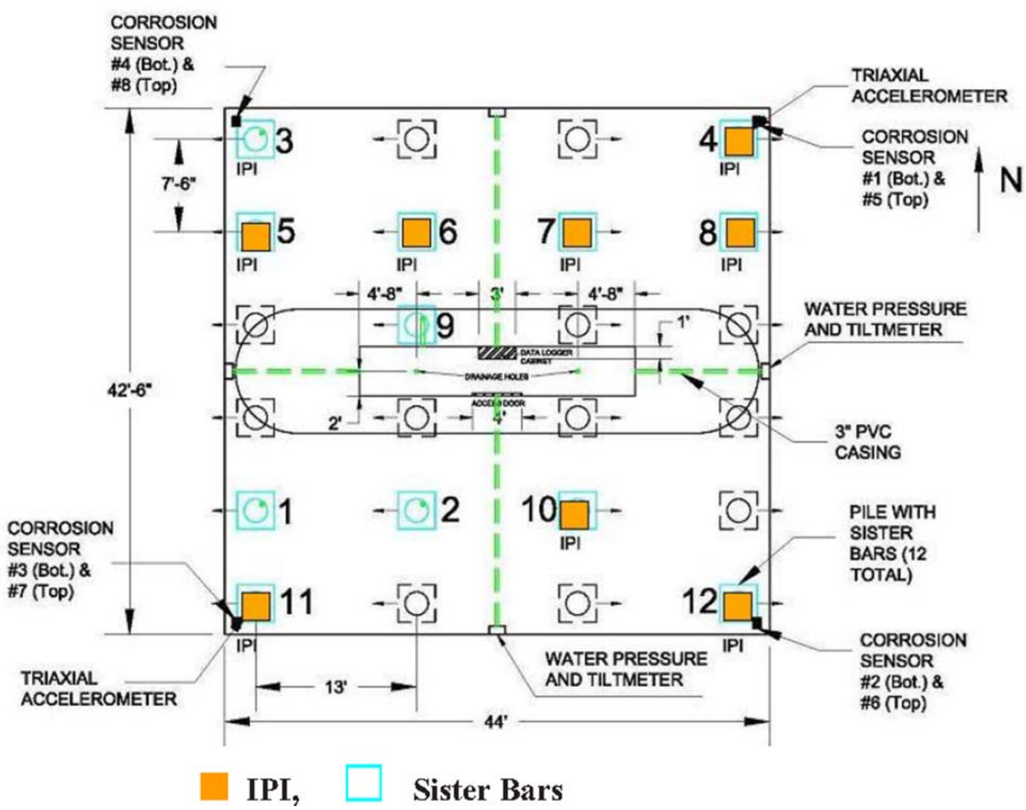


Figure 4.8: Instrumentation on piles and pile cap (Abu-Farsakh et al. 2010)

Pile instrumentation included the installation of MEMS In-Place Inclinometers (IPI) to monitor pile inclination/movements perpendicular to its axis. Six MEMS IPI sensors were installed in PVC casing per instrumented pile, as shown in Figure 4.9.

Figure 4.9: Installed IPI Casing (Abu-Farsakh et al. 2010)

Selected piles were instrumented with resistance-type sister bar strain gages for monitoring strain distribution in piles during lateral load test, as show in Figure 4.10. Installed strain gages determined the axial load and bending moments of the instrumented piles.

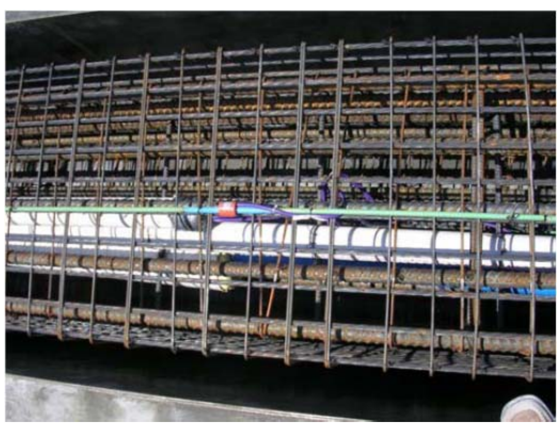


Figure 4.10: Installed Sister Bar Strain Gages (Abu-Farsakh et al. 2010)

Pile cap instrumentation consisted of two triaxial accelerometers placed on top of the pile cap to measure the dynamic behavior during the long-term monitoring of the pier. The accelerometers were also used as a trigger mechanism to activate data collection/saving for other sensors under any event. In addition, four uniaxial MEMS tilt-meters were installed to measure the rotation of the pile cap during long-term monitoring. Water pressure transducers were placed on the pile cap to measure water wave force during selected events. Embedded corrosion instrument sensors were installed to measure the corrosion progress during long-term monitoring.

4.4 Monitoring of Internal Relative Humidity

Internal relative humidity (IRH) is a key parameter related to the early age and long-term performance of concrete (Livingston, 2002). At the early stages of concrete hardening, the IRH of concrete can be correlated with self-desiccation, creep, and shrinkage (Mehta and Monteiro, 2006). Long-term durability performance problems related to concrete deterioration and affected by IRH include alkali-silicate reaction (ASR) (Klahorst et al., 2005), delayed ettringite formation (DEF) (Graf , 2007), and corrosion of steel reinforcements (Andrade et al.,1999;Moriconi and Naik, 2010). Due to its importance, the monitoring of IRH over time by the embedded sensors is an attractive option to observe the concrete performance. Detecting the initiation of the corrosive process in an infrastructure will have significant value to architects, maintenance engineers, operators, and owners, as targeting specific zones susceptible for corrosion since with early detection and early intervention, the maintenance costs will decrease (Vaisala, 2006;Moriconi and Naik, 2010).

There are no widely accepted commercial systems for continuous and distributed monitoring of IRH (Livingston 2002); the IRH probes/sensors are available and can be placed in freshly placed concrete (Vaisala 2006, Moriconi and Naik, 2010); for hardened concrete, these probes require disturbing the concrete structures for installation. Other technologies include electronic sensors that rely on digital signals and fiber optics placed throughout the structure (Livingston, 2006).

Monitoring Electrochemical Potential and Steel Corrosion

The monitoring system based on embedded electrodes (EEMS) was used on several structures (Moriconi and Naik, 2010); gathered data were sent to a recording device for a remote reading at one central monitoring center via a communication link. The developed monitoring system can be moved between different locations so that several bridges and structures can be monitored (Table 4.3).

EEMS, with reference electrodes made of oxide-activated titanium bar segments, was used to measure the free-corrosion potential of concrete. These reference electrodes (Figures 4.11-4.13) were calibrated by a saturated calomel electrode (Moriconi and Naik, 2010). The measuring electrodes were steel bar segments, which were fixed to the reinforcing steel bars by mechanical connections or welding. Silicone-insulated cables were used to electrically connect each electrode leading to the measuring apparatus. The peripheral device for remote reading was constituted by an electronic interface for data processing and storage (equipped with data acquisition software), telephone line interface for data transmission, programmed acquisition interface card, data transmission modem, battery and power supply equipment, and power transmission and distribution safety equipment, Figure 4.11 (Moriconi and Naik, 2010).

It was reported that the location of EEMS monitoring points in the structure was selected based on the geometry and the specific exposure conditions. The monitoring system has proved to be effective in water reservoirs (Figure 4.13), where EEMS provided effective warning, and a spike in the potential measurement suddenly appeared. This alert was very useful for detecting the failure location. After the reservoir was emptied, the free-corrosion potential measurement dropped to normal levels (Moriconi and Naik, 2010). It was proved that EEMS can detect the presence of conditions promoting corrosion, as well as other related deterioration process in the structures (Moriconi and Naik, 2010).

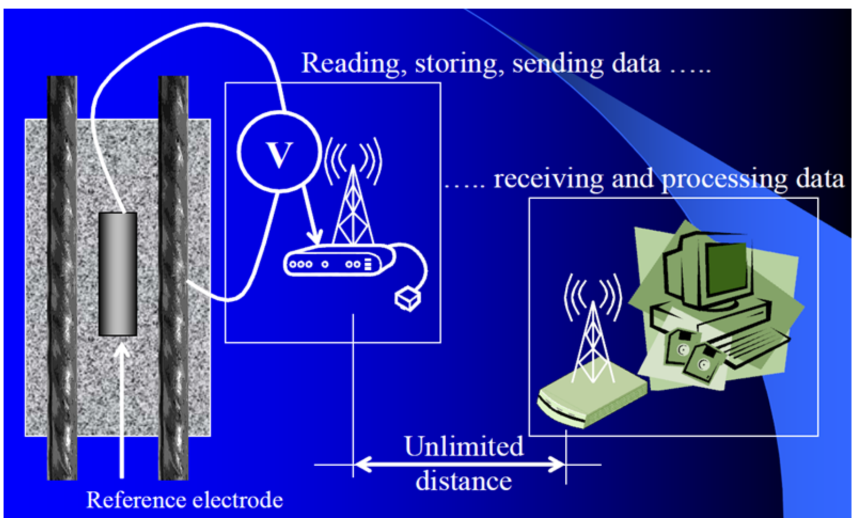


Figure 4.11: The schematics of IRH monitoring system (Moriconi and Naik, 2010)

Figure 4.12: The installation of IRH sensor (Moriconi and Naik, 2010)

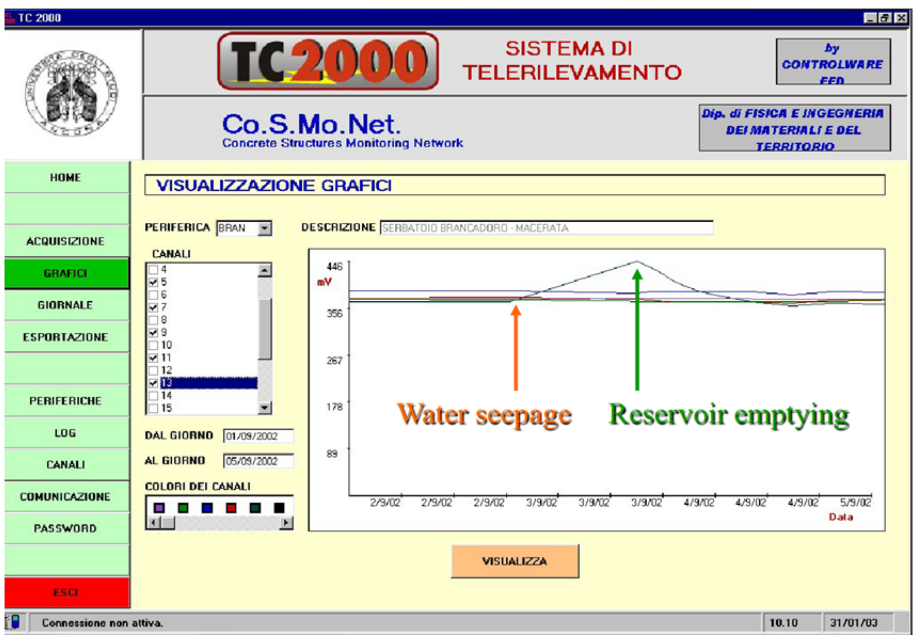


Figure 4.13: The output screen of IRH monitoring system (Moriconi and Naik, 2010)

Table 4.3: IRH Performance record (Moriconi and Naik, 2010)

	Car park	Wastewater treatment station	Elevator	Drinking water reservoir	Bridge
Year of original construction	2002	2003	1960s	2001	2007
Year of installation of the monitoring system	2002	2003	2001	2001	2007
General description of the structure	Multilevel reinforced concrete structure	Concrete construction, reinforced with galvanized steel	Reinforced concrete structure	Multiple compartment concrete construction reinforced with galvanized steel	Reinforced concrete pile and deck slab
Performance record of the monitoring system	The monitoring system is able to continuously transmits data with time of the corrosion-potential of the reinforcing steel bars, which can be plotted as a Microsoft Excel file at any time on demand. However, every time a corrosion-potential change occurs higher than a prefixed threshold, an alarm appears at the remote server located at the university and an e-mail is sent.				
Repairs and rehabilitation activities			A potential spike appeared in December 2001 corresponding to an electrode located on the top of the structure. On checking, it was attributed to a lightening, which polarized the corresponding steel bar and caused a power cut out.	A potential increase was detected corresponding to an internal wall between a water compartment and the operating room. After emptying the compartment, a potential decrease back to the original values was monitored and a failure in the waterproofing treatment was detected.	
False alarms	No	No	No	No	No

Application of Fiber Optic Sensors

It was demonstrated that the fiber optics FBG strain sensor can be converted to a relative humidity sensor by coating the grating region of the fiber with a hygroscopic polymer that shrinks or swells in response to changes in humidity, Figure 4.14 (Livingston, 2006). As the coating expands and contracts it applies strains to the FBG, which can be detected. This technique was realized by a team from the University of Strathclyde (Michie et al., 1995), and US FHWA (Livingston, 2006). The design concept of sensor used in FHWA research is illustrated by Figure 4.14.

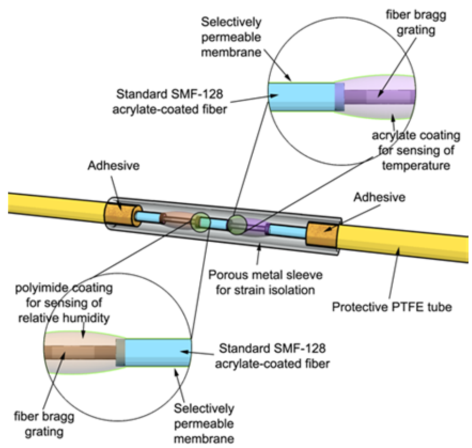


Figure 4.14: Design of the internal RH Sensor for concrete (Livingston, 2006).

A schematic of the signal conditioning and readout system that converts strain in the FBG sensor to digital data is illustrated in Figure 4.15. The reflected light from the FBG sensor was detected by a Fabry-Perot interferometer SM 125. This unit incorporates a narrow band-pass filter that sweeps over the range of wavelengths, and a photo detector that measures the intensity of the filtered light so that the intensity can be displayed as a function of wavelength (Livingston, 2006). The software in the SM125 can calculate the wavelength with an accuracy of ~ 1ρm. The collected data was recorded by Lab View® software and analyzed in Excel (Livingston, 2006).

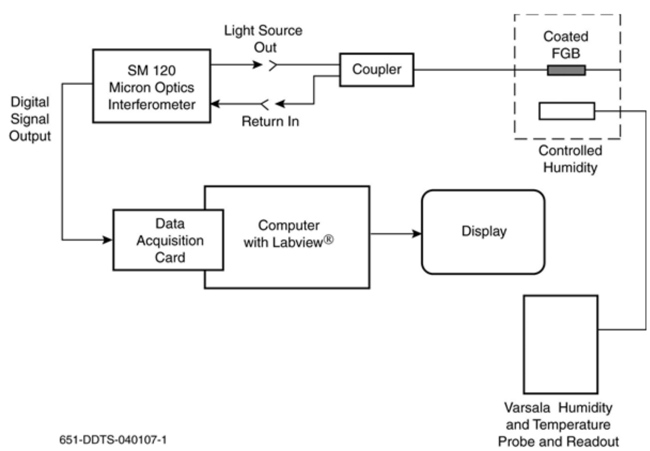


Figure 4.15: Schematic view of FBG signal conditioning and readout (Livingston, 2006)

The performance of developed IRH sensors in the field was tested in the concrete deck of a bridge under construction near Las Cruces, New Mexico (Figure 4.16). It was demonstrated that IRH sensors collected reliable data with sensitivity greater than ± 0.1 % RH over the range 70 to 100 % RH. The results indicate that it is feasible to manufacture internal RH sensors based on FBG. It was also demonstrated that sensor response is linear with a resolution of ~ 1%, which is comparable with or better than other methods. It was concluded that with the availability of IRH sensors, there are many potential applications, including bridge decks, columns, piers, foundations, pavement slabs, and other highway structures (Livingston, 2006). There are also potential commercial applications in other fields such as buildings, airport runways, dams, and other civil engineering structures. Besides these field applications, the sensors can be used to improve the standards and methods for concrete testing such as shrinkage and alkali-silica reactivity tests (Livingston, 2006).

Figure 4.16: Interstate I-25 bridge at Dona Ana, New Mexico (Livingston, 2006).

4.5 Self-Sensing "Smart" Cement-Based Composites

Piezoresistive cement-based materials are a relatively new group of smart materials produced by adding carbon fibers or nanoparticles (Lynch and Hou, 2005; Fu and Chung, 1996; Shen and Chung, 1996). These composites exhibit piezoresistive properties, making self-sensing applications possible (Chen et al., 2004a; Wen and Chung, 2000 and 2005). As determined in the past decade, carbon fiber-reinforced concrete and cement mortar containing nano-sized semiconductors can sense compressive or tensile stress both in the elastic and inelastic regimes (Wen and Chung, 2005).

The use of “smart” materials that self-monitor their stress and strain conditions is an attractive option for monitoring the health of the civil infrastructure. As defined by Phares et al. (2005), a *“Smart”* technology is “one in which *the system systematically reports on the condition of the structure by automatically making engineering-based judgments, records a history of past patterns and intensities, and provides early warning for excessive conditions or for impending failure without requiring human intervention*. These features make the system capable of providing and facilitating *self-diagnostic, real-time continuous sensing, advanced remote sensing, self-organizing, self-identification, or self-adaptation (decision making and alarm triggering) functions.”*

<u>Nanomaterials for smart applications</u>

The piezoresistive effect in cement-based applications is expected to be a valuable tool for measuring stress and strain with the material. The change in the electrical resistivity of a material (piezoresistive effect) occurs when the mechanical stress is applied. The main goal for various types of nanomaterials used in cement-based composites is to obtain the desired piezoresistive response by adding carbon fiber, carbon black and multi-walled carbon nanotubes.

Carbon fiber-reinforced cement may function as a piezoresistive strain sensor (Wen and Chung, 2000; Zheng et al., 2004b). Chung and co-workers (1996, 1999, 2000, and 2005) carried out a series of investigations on the carbon fiber-reinforced, cement-based composite. It was demonstrated that the introduction of carbon fibers into cement composite decreases the electrical resistivity, due to the high conductivity of the carbon fibers compared with cement. Even a low volume fraction of carbon fibers can be effective providing smart materials with low costs, good workability, and high compressive strength. In addition to providing the strain-sensing ability, adding carbon fibers to cement increases the tensile and flexural strength, tensile ductility, and flexural toughness, and decreases the drying shrinkage (Chen and Chung, 1996 and 1999), thereby making self-sensing feasible. This is proposed by embedding a waterproof piezoelectric patch with wire leads into a small concrete block (Song et al., 2004 and 2005). The sensing aggregates are then embedded at the desired locations in the concrete structure before casting.

Ou and Li (2006 and 2008) used a carbon black-filled cement-based composite as a self-sensing material in a civil engineering infrastructure, Figure 4.17. A piezoresistivity model was proposed to predict the strain-sensing property of carbon black-filled cement-based composite. The conductive network in the composites was assumed to be composed of randomly distributed tunnel resistors, which are formed by each adjacent particle, Figure 4.18.

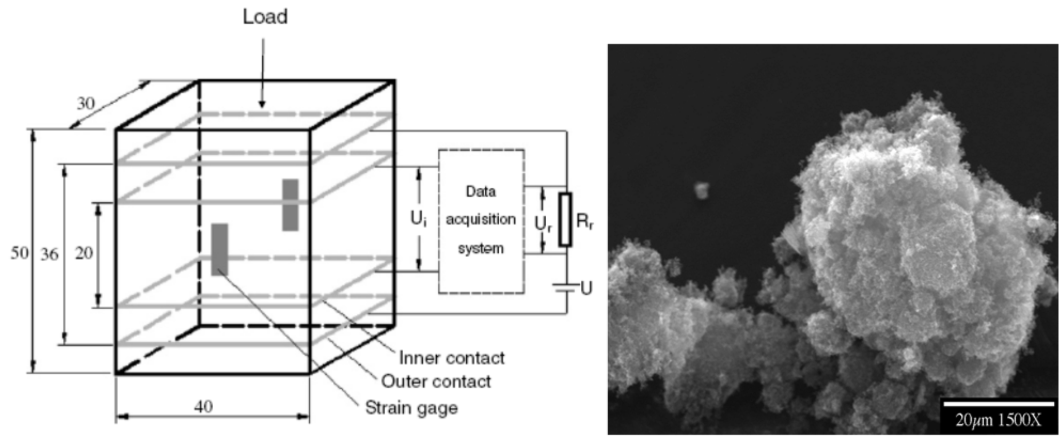


Figure 4.17: Schematics of the testing unit and structure of carbon black particle (Ou and Li, 2006 and 2008)

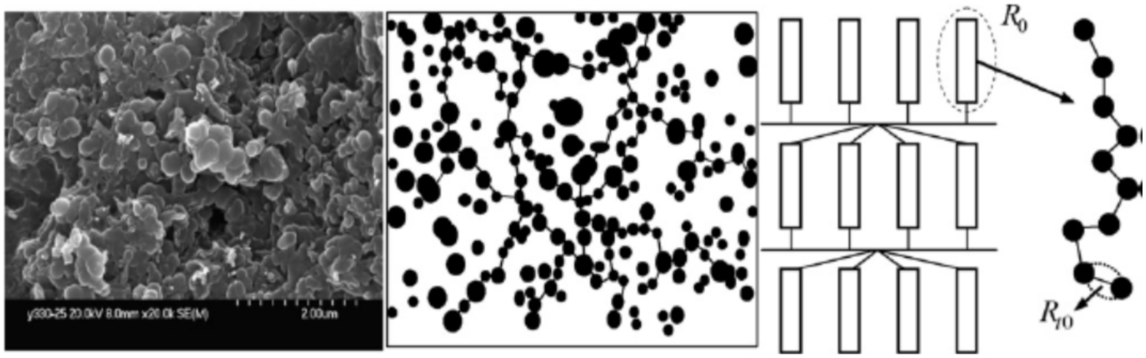


Figure 4.18: SEM photos of smart material and the conductive network model (Ou and Li, 2006 and 2008)

Yu et al. (2009) proposed a self-sensing material by introducing multi-walled carbon nanotubes (CNT) for traffic monitoring. The cement composite was filled with multi-walled carbon nanotubes whose piezoresistive properties enable the detection of mechanical stresses induced by traffic flow. The sensing capability of the self-sensing CNT/cement composite was explored in laboratory tests and road tests, Figure 4.19.

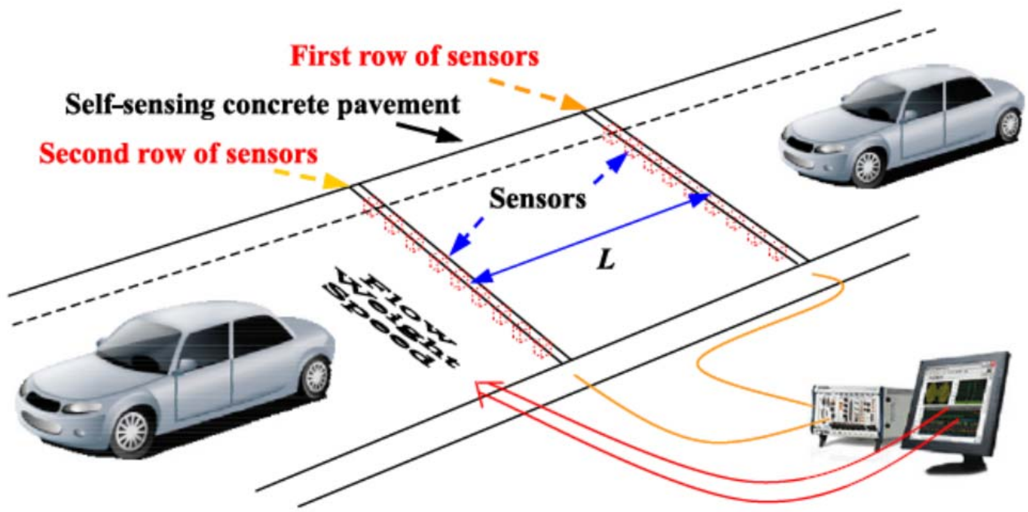


Figure 4.19: Schematics of self-sensing composite in traffic monitoring (Yu, 2009)

Corrosion of concrete steel reinforcements is one of the main causes for the short service life of concrete structures (Carkhuffet al., 2003; Zheng et al., 2004a and 2004b;Nanni et al., 2009). Nanni et al. (2009) presented a self-monitoring nano-composite material made of glass fibers in the form of a reinforced polymer rod used as a reinforcing element and sensor in concrete, Figure 4.20. The sensitive part of such element consists of carbon nanoparticles incorporated within the epoxy matrix, which imparts the variation of electrical resistance under loads.

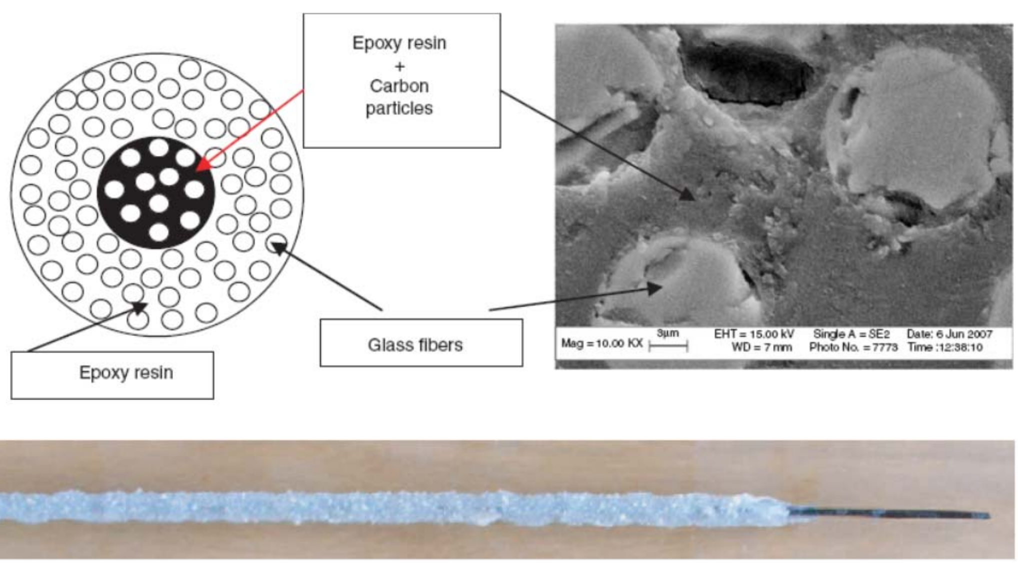


Figure 4.20: A CF-GFRP rod with internal conductive CnP-GFRP and external glass fibers (Nanni et al., 2009)

Nano-colloids and nano-structures (e.g., carbon nanotubes) can offer new opportunities to tune the macro-scale material properties (Loh et al., 2006). Bio-inspired materials, including forisomes, represent another great opportunity to design novel sensors for structural health monitoring (Pickardet al., 2006). With the limitations of available sensors for structural health monitoring systems, self-sensing, smart cement-based materials using nanotechnology offer new tools for the precise tailoring and miniaturization of sensors and systems designed for structural health monitoring applications.

<u>Nanocomposite Sensing Skins for Distributed Structural Sensing</u>

Lynch et al. (2009) reported on the design of a novel stress-sensing material based on single-wall carbon nanotubes (SWNT) and polyelectrolytes (PE) to create a homogenous SWNT-PE composite film with superior mechanical strength and with electrical conductivities that change in response to strain and tearing. This material is capable of distributed sensing using Electrical Impedance Tomography (EIT).

The distributed sensing properties of the nano-composite thin film were validated by the set of experiments by impact testing, Figure 4.21. SWNT-PE film was deposited on a thin steel plate to produce a large structural specimen (Lynch et al., 2009). After deposition of the sensing skin, copper electrodes were attached to the plate along its boundary with electrodes on each of the four sides. The sensing skin-coated steel plate was then clamped into an impact apparatus, in which a pendulum is used to impact the plate (Figure4.21a). It was demonstrated that SWNT-PE nanocomposites can be used as a distributed sensing skin (Lynch et al., 2009).

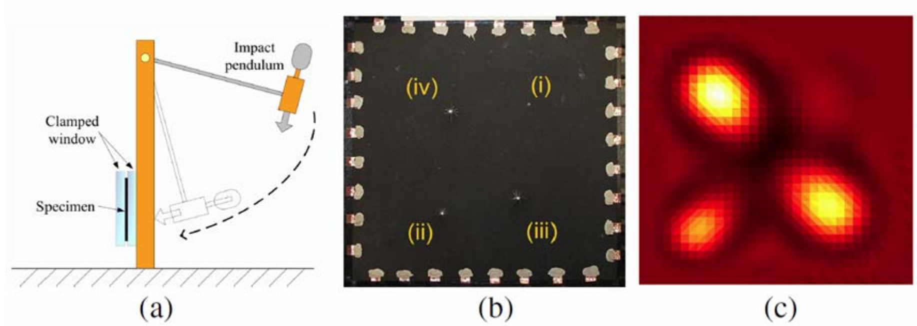


Figure 4.21:(a) Impact test apparatus; (b) four impacts upon the sensing skin coated plate element; (c) corresponding EIT conductivity map with percentage change in conductivity (Lynch et al., 2009).

Strain-Sensing Materials (SSM) Based on Surface Wave Propagation

Zoughi and Kharkovsky (2008) have used microwaves (300 MHz to 30 GHz) and millimeter (30 GHz to 300 GHz) waves for detecting cracks. In the reported application, a layer of dielectric paint was placed on a steel member with a preformed defect, and EM waves were emitted and received by two closely placed antennas. The normal EM wave transmit is disturbed near the defect in the base metal. The disturbance of the EM wave must be detected in the frequency domain, thereby requiring specialized equipment.

Recently, the research team at UW-Milwaukee (Nevers et al, 2011) proposed an innovative concept for stress-sensing material (SSM) for potential use as a cost-effective bridge health monitoring system. This SSM consists of a thin layer of electromagnetic (EM) wave-guiding material applied on a steel member, an EM wave transmitter, and a signal receiver. The fundamental concept of the SSM is similar to that of fiber optic sensors, except that fiber optic sensors usually detect the phase change of an optical wave (i.e., high-frequency EM wave in multiple THz), as reported by Gomez et al. (2009), while a lower frequency (e.g., around 40 MHz) EM wave is used in the proposed SSM technique.

The advantage of SSM is that with lower frequencies, well-established technology developed for wireless communication may be used to detect the disturbance of the EM wave caused by strains in the base steel. Importantly, the amplitude of the EM wave rather than the phase changes can be used for strain detection, leading to an economical and practical set-up for response monitoring (Zoughi and Kharkovsky, 2008). The envisioned application of such sensor technology is schematically shown in Figure 4.22 for monitoring a deck truss bridge: a layer of SSM is applied to steel members (both primary members and secondary members) in a manner similar to an anti-corrosive paint; EM wave transmitters and receivers are located at the joints to emit/receive the EM wave and detect changes. The obtained information may be sent to engineers via wireless communication devices.

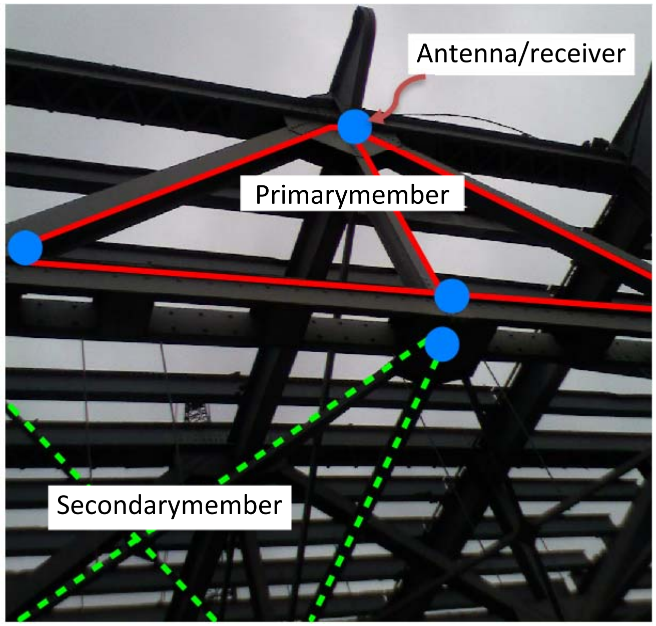


Figure 4.22: Schematic of electromagnetic wave sensors on deck truss bridge (Zhao, 2007; Nevers et al, 2011).

SSM based on the principles of 40 GHz surface wave propagation were developed (Nevers et al, 2011). With a lower frequency, the amplitude of the EM wave can be used for the targeted measurement with an expectation to eliminate the need for expensive specialized equipment for phase detection. In the study at UW-Milwaukee, various materials with different dielectric, adhesion and mechanical properties were tested (Nevers et al, 2011). If energy absorption is high, the signal transmitter and receiver need to be placed close together, as in the study by Zoughi and Kharkovsky (2008). The Low-Density Polyethylene (LDP) with desirable characteristics (i.e., a dielectric constant of around 2.2 and a loss tangent of 0.00065, indicating very low absorption) and high ductility was used to demonstrate the concept of the proposed sensor (Nevers et al, 2011). The verification tests for the SSM concept were conducted on steel coupons with low-density polyethylene adhered to the steel using acrylic adhesive (Nevers et al, 2011).The coupon specimens were sized proportional to that of the standard tension coupons per ASTM standards, as shown in Figure 4.23.

Figure 4.24 shows the EM wave amplitude against the strain applied to the specimen with a LDF layer. The EM wave amplitude generally decreases with an increase in the strain applied to the specimen up to a strain of 0.035%. This study proved viable the use of electromagnetic (EM) surface waves within the millimeter wave range in sensing strains in steel members (Nevers et al, 2011). As the EM surface wave is propagating through the dielectric material, the change in the amplitude of the wave, representing the energy being transmitted, can be detected and correlated with the strains of the base metal. The developed sensor can be an innovative and practical method for use in the structural health monitoring of steel bridge structures.

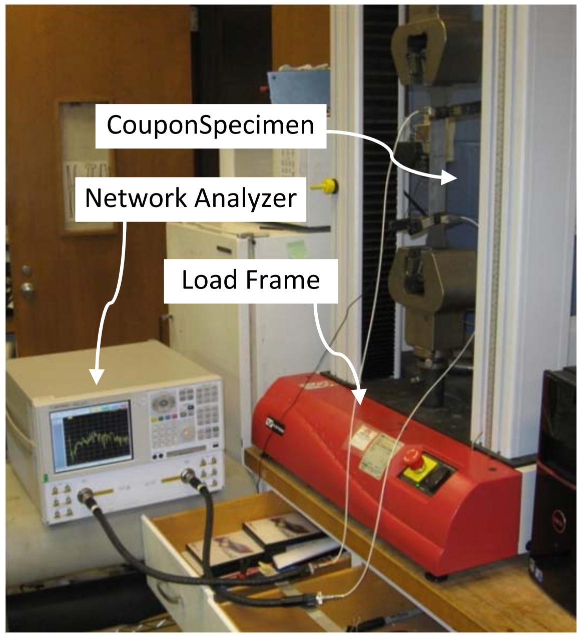


Figure 4.23: Experimental test setup for SSM (Nevers 2010)

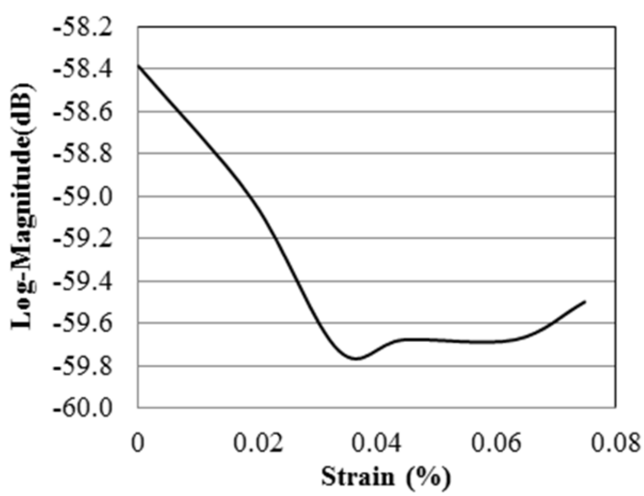


Figure 4.24: EM wave amplitude vs. strain (Nevers 2010)

4.6 MnROAD Pavement Test Facility

The MnROAD test facility was originally constructed in 1994 near the town of Albertville, Minnesota, approximately 40 miles northwest of Minneapolis at a cost of $25 million dollars. The facility was designed to include interstate and low-volume test sections, and was constructed and maintained via a partnership between the Minnesota Department of Transportation (Mn/DOT) and the Minnesota Local Road Research Board (LRRB). The general layout of the current MnROAD facility is shown in Figure 4.25. The facility was originally divided into 40 test cells representing a variety of pavement materials and designs.

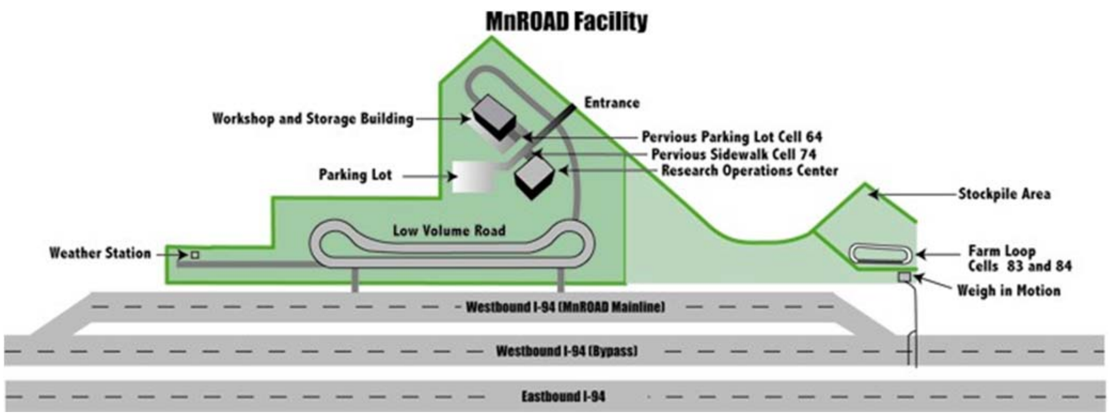


Figure 4.25: MnROAD Facility Layout (http://www.dot.state.mn.us)

The mainline MnROAD test section includes a 3.5 mile section of westbound I-94 and was originally designed for five- and ten-year life expectancies, and contained 23 test sections made up of 14 asphalt and 9 concrete pavements. The low volume road loop was originally designed for a three-year life expectancy and contained 17 test sections:8 asphalt, 5 concrete, 2 treated aggregate and 2 aggregate surfaces.

The test sections were heavily instrumented, sampled, and tested and provided researchers with a valuable resource to evaluate pavement performance under actual conditions of traffic, environment, and materials. A key design feature of the mainline MnROAD facility was the ability to divert traffic back onto the original westbound lanes of I94, thereby providing a safe zone for testing/repairs without disruption to the driving public.

Since the original construction in 1994, a many test sections have been removed and replaced with additional sections to greatly expand the original scope of the study. Figure 4.26 provides a schematic of the layout and instrumentation plan for the recently constructed composite pavement section.

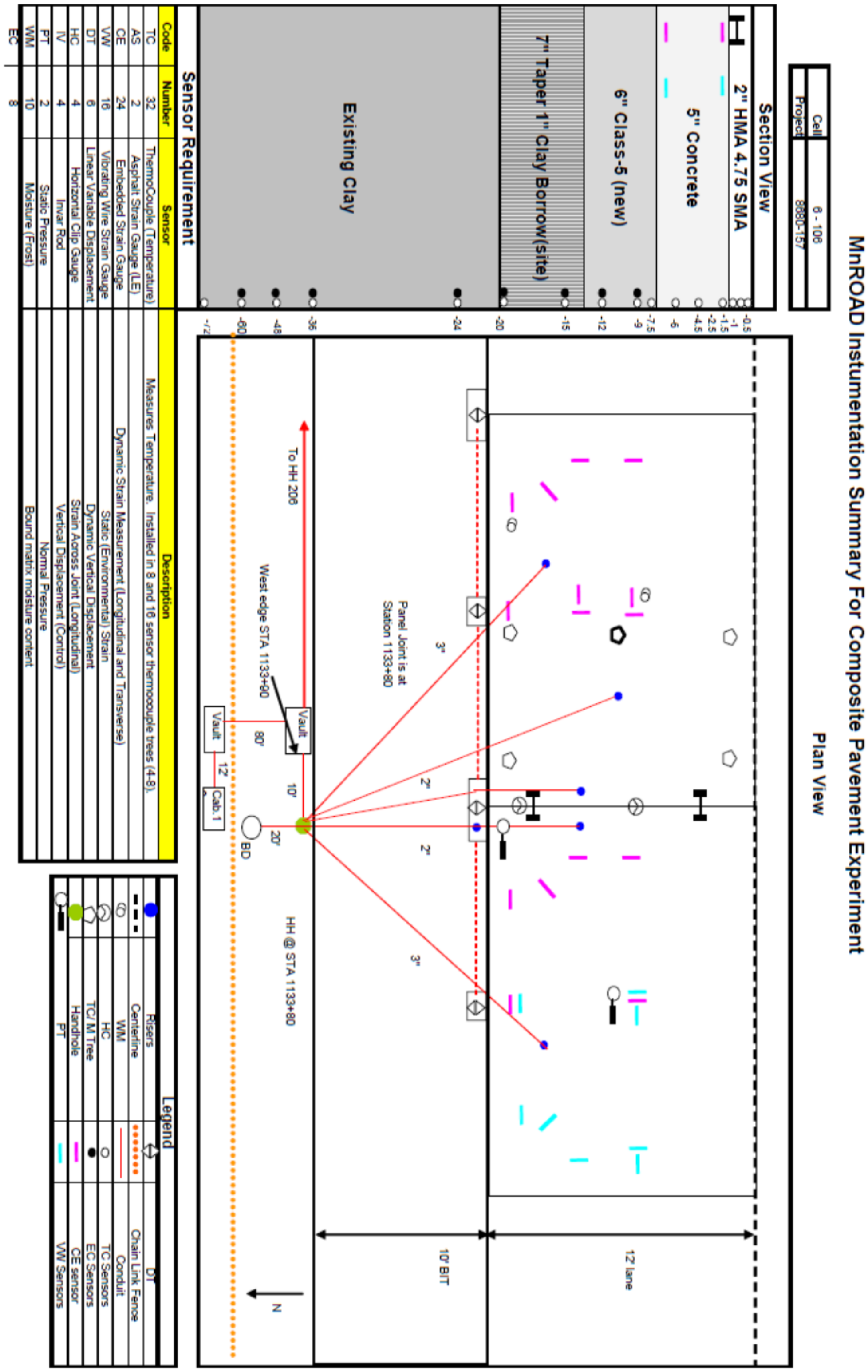


Figure 4.26: MnROAD composite pavement test layout (http://www.dot.state.mn.us)

4.7 Marquette Interchange

The Marquette Interchange, located in downtown Milwaukee, Wisconsin, was completely reconstructed from 2004 to 2009. The North Leg of this project, which included the northbound and southbound lanes of I-43, incorporated a perpetual HMA pavement that was designed to provide 50+ years of service with minimal maintenance. The Wisconsin Department of Transportation (WisDOT) funded a detailed experiment to instrument a portion of the perpetual HMA pavement to document the load-induced stresses and strains within this pavement structure and to validate this pavement design concept.

A short section of the outer northbound lane was instrumented using a variety of sensors to monitor the critical tensile strains produced by moving traffic loadings in combination with environmental factors. Weigh-in-motion (WIM) and wander strip systems were used to document the speed, placement, and magnitude of each passing axle load. A roadside weather station provided information on air temperature, wind speed and solar radiation. Figure 4.27 provides a schematic of the strain and pressure sensor layout for this project.

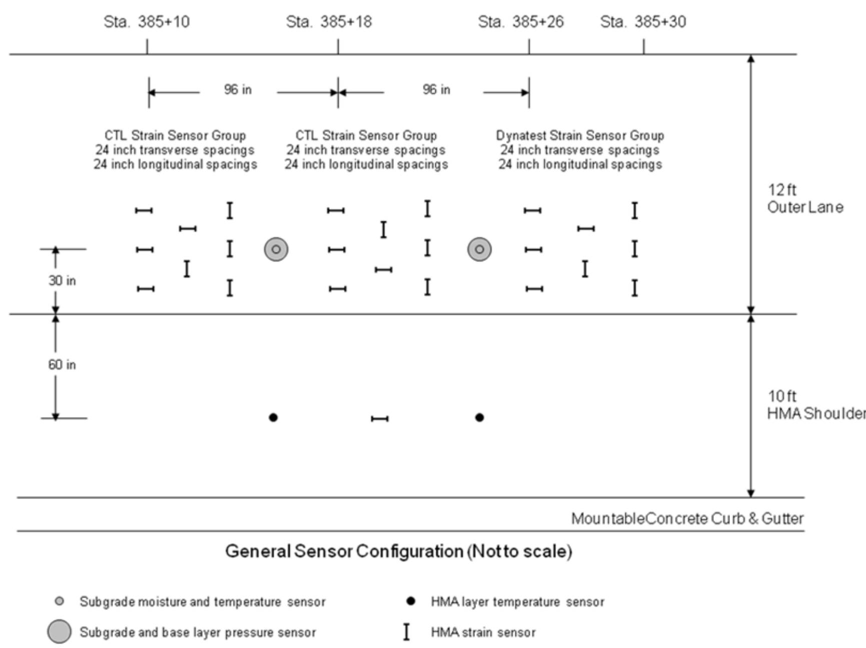


Figure 4.27: Marquette Interchange test layout

Chapter 5

Cost of Infrastructure Health Monitoring

This chapter presents cost figures of Infrastructure Health Monitoring (IHM) system components. The purpose of presenting cost estimates is to provide general idea about the cost of such components. More accurate cost estimates are provided for instrumentation plans provided in the final report.

5.1 Costs of Infrastructural Health Monitoring

The costs associated with the design, installation, and monitoring of SHM systems varies greatly, and is dependent on the following factors:

- Type and size of structure
- Number and type of sensors
- Static/dynamic measurements
- Site access ease/difficulty
- Wired/wireless sensors
- Isolated individual sensors/ distributed sensors
- Manual/automated data acquisition systems
- Environmental and vandalism protection systems
- Data transmission methods/speed/frequency
- Real time/Stored data
- Local/remote data storage and retrieval

The total cost of a SHM system includes:

- Sensor costs
- Sensor installation cost
- Wiring costs
- Travel costs for installation personnel
- Environmental (lightening) and vandalism protection
- Monitoring system hardware
- Monitoring system software

The total cost per unit sensor depends on the number of sensors. Analysis of data from a study by the Applied Geomechanics, Inc. (AGI) indicates that per-sensor total cost can range as follows:

- For a 50-sensor system: approximately $1,200-$4,000 per sensor
- For a 100-sensor system: approximately $1,300-$2,500 per sensor
- For a 1000-sensor system: approximately $450-$1,300 per sensor

Figure 5.1 below from an AGI publication shows the detailed cost breakdown for different systems. The following terminology is used: Vibrating Wire Strain Gage Systems (VWSG), Electrical Resistance Strain Gage System (ERSG), Fiber Bragg Grating Fiber Optic Systems (FBG FO), and Distributed Strain Temperature Fiber Optic Systems (DST FO).

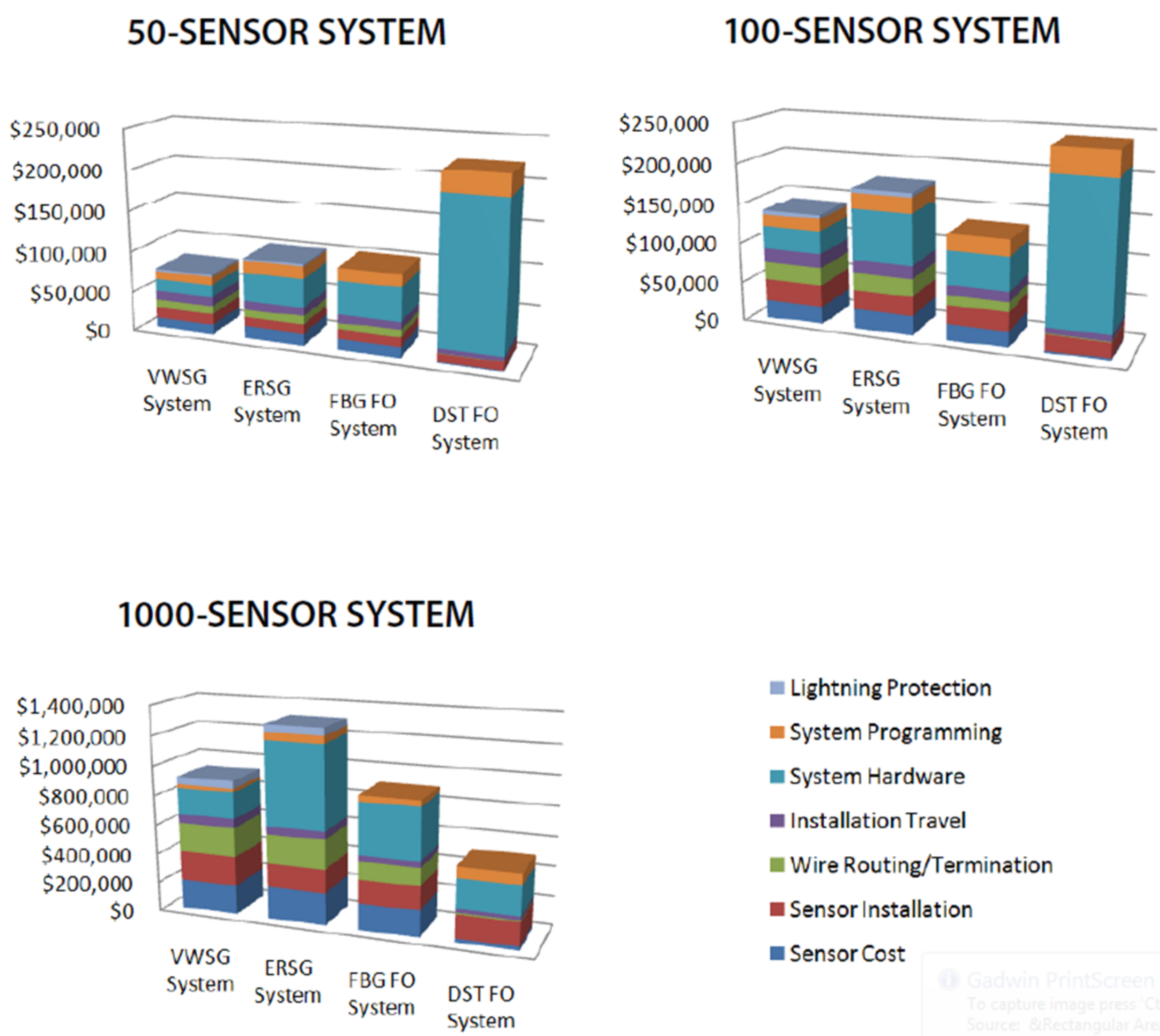


Figure 5.1: Comparative costs of health monitoring systems for different sensors and sensor types (Courtesy of Mr. Tom Weinmann, Applied Geomechanics, Inc.)

5.2 Cost of Sensors

Table 5.1 presents the prices for various sensors to provide a general idea about their costs. It should be noted that sensor technology is advancing in an accelerated rate, where the quality/ accuracy is going up and prices are going down.

5.3 Cost of Data Acquisition Systems

Table 5.2 presents the prices for data acquisition systems to monitor a bridge or retaining wall.

5.4 Cost of Web Based Data Viewing

The IHM website can be launched by the owner of the structure being monitored; alternatively, existing websites developed by consultants can also be used. Table 5.3 presents such cost estimates, including software.

5.5 Cost of Labor

Cost of labor can be divided into the following:

1. Fees to develop instrumentation plan/design, constructions drawings, etc. Typical fees range from $5,000 to $10,000.
2. Installation costs depend on the number of visits by the installation contractor during construction. Several trips to the site may be required, depending on project type. Table 5.4 presents installation cost estimates for a typical bridge with sensors, as presented in Table 5.5.
3. Maintenance cost accounts for incidents that may affect the system such as electrical storms or vandalism. Maintenance can be performed in-house when the owner has significant number of systems. The cost for consultants per maintenance trip ranges between $2,500 and $5,000.
4. Data interpolation cost. Depending on the use of the system, data interpolation may require an engineer to look at data every day or once per month.

Table 5.1: Typical costs of various sensors

Sensor	Type	Manufacturer	Cost	Application	Additional Info
Strain Gauge	Vibrating Wire Strain Gauges (VWSG)	Geomechanics Geokon Slope Indicator RST Instruments Smartec Encardio Rite HBM	$65-$90	Strain gauges can be welded to steel surfaces to measure strains or can be embedded within concrete to measure internal concrete strains. They are not suitable for dynamic (rapid) strain measurements.	
	Electrical Resistance Strain Gauges (ERSG)	Vishay Micro Measurements Omega Micro Sensor Technology Endevco Corp.	$5-$10 each	Changes in electrical resistance are determined to correspond with length changes or strains and are measured through a simple Wheatstone bridge. Types of ERDG include bonded wire, unbonded wire, bonded foil, semiconductor and weldable strain gauges	
	"Sister" Strain Gauges or Rebar Strainmeters	Geokon Applied Geomechanics Marton Geotechnical Services LTD RST Instruments	$150-$500	These gauges are embedded within concrete to measure strains of bridge girders, concrete piles, tunnel linings, mass concrete structures, and retaining walls.	
	Distributed Fiber Optic Strain Gauge	Geokon Applied Geomechanics	$245	Used in environments where it is difficult to use conventional strain gauges because of space considerations or high levels of electrical interference. They consist of long optical fibers which are attached or embedded in structures.	Requires fiber optic cable and loctite bond adhesive
Accelerometers	Piezoelectric Accelerometer	Endevco PCB Bruel & Kjaer Omega ST Microelectronics Measurement Specialties	$400 -$600 each	Uses piezoelectric effect of certain materials to measure dynamic changes in mechanical variables such as acceleration, vibration, and mechanical shock.	requires a constant current source, calibration is required once per year
	Piezoresistive Acelerometer	PCB	$400-$1000	Used to measure constant, transient, and periodic accelerations.	
	Seismometers		$400-$700	Measure and record motions in the earth's crust in response to earthquakes and volcanoes.	

Table 5.1 (cont.): Typical costs of various sensors

Sensor	Type	Manufacturer	Cost	Application	Additional Info
Displacement Transducers	Linear Variable Differential Transducer (LDVT)	Trans-Tek Geokon Macro-Sensors Measurement Specialties	$80-$150	Used to measure linear displacements of structures such as bridge slabs or bridge superstructures.	Requires little to no maintanence if used properly. Requires data acquisition system.
	Linear Pontetiometer	Applied Geomechanics	$300	Used as a resistor with a sliding contact that formsan adjustable voltage divider. Used in place of LDVTs for their ruggedness, simplicity, and low cost.	
	Extensometers	Geokon Applied Geomechanics	$3,500	Used to measure small or large changes in length of an object. Different types of extensometers include single point, multiple point, and tapes extensometers.	
	Crack Gauges or Joint Meters	Geokon Geotest PRG Durham Geo Slope Indicator	$475-$1100	Used to measure movement across the two sides of an existing crack.	Additional data acquistion machines required at $500-$1300
	Global Positioning System (GPS)		$500-$5000	Compute 3-Dimensional position and movement	
	Fiber Optic Sensors	Banner Keyence Measurement Solutions MTI Instruments	$200-$400	Used as a sensing element or as a relay signal from a remote sensor.	Fiber optic cable (approx $1-$2/ft)
Tiltmeters/Inclinometers	Vertical In-Place Micro-Electro-Mechanical Systems (MEMS)	Geokon	$630-$840	Remotely measure lateral movement of soil and rock or deflection of piles or retaining walls	Requires mounting bracking, data aquistion and data aquistion software
	Horizontal In-Place MEMS Inclinometers	Geokon	$630-$840	Remotely measure lateral movement of soil and rock or deflection of piles or retaining walls	Requires mounting bracking, data aquistion and data aquistion software
	In-Place MEMS Tiltmeters	Geokon	$630-$840	measures single of biaxial planes perpendicular to its surface	Requires mounting bracking, data aquistion and data aquistion software

Table 5.1 (cont.): Typical costs of various sensors

Sensor	Type	Manufacturer	Cost	Application	Additional Info
Temperature Sensors	Thermocouples	Omega	$90-115	Used to measure very large range temperature gradients	
	Resistance Temperature Sensors (RTD)	Omega		Used to measure temperature with high accuracy and over large range temperature gradients by tracking changes in resistance with change in temperaturs	
	Vibrating Wire Temperature Sensor	Slope Indicator Applied Geomechanics Geokon	$202	Used to measure temperatures in and around dams, concrete structures, geothermal wells, and landfills	
	Infrared Temperature Sensors	Omega	$65-260	Detects people and fire by using IR spectrum rather than visible light	
	Thermal Imaging Cameras		$2500-$8000	Used to detect very small difference in thermal radiation	
	Distributed Fiber Optic Temperature Sensor	Extech Applied Geomechanics Omega Slope Indicator Geo-Instruments Geokon Raytek Apogee Extech	$1000-$3000	Measure temperature using fiber optic cables and is capable of obtaining thousands of accurate high resolution temperature readings	
Load/Pressure Cells	Earth Pressure Cells	Omnisens	$300-$800	Used to measure earth bearing pressures on foundations, piles, or footings	
	Tension and/or Compression Load Cells	Geokon Omega RST Instruments LCM Systems	$350-800	Monitors tensile or compressive forces on a structure	
	Vibrating Wire New Austrian Tunnel Method (NATM) Stress Cells	Futek	$450-$600	Measure stresses in concrete or shotcrete linings in underground structures	
Piezometers	Vibrating Wire Piezometers	Slope Indicator	$340	Used to monitor water or pore pressures in a soil	
	Fully Grouted Multi-point Piezometer String	Slope Indicator	$400	Allow for multiple Vibrating Wire Piezometers to be placed on a single cable	

Table 5.1 (cont.): Typical costs of various sensors

Sensor	Type	Manufacturer	Cost	Application	Additional Info
Settlement Sensors	Vibrating Wire Liquid Settlement System	Roctest	$9,600	Monitor settlement or heave in soils of embankments or earth or rockfilled dams	Additional cost of Saturation at the factory $160.00 Reference liquid reservoir $265.00 Twin Tubing $7.70/m
	Multi Cell Liquid Settlement System	RST Instruments		Monitor settlement or heave in soils and is only limited by the local conditions	
Ice Detection Systems		Campbell Scientific	$7,000	Monitor ice formations	
Corrosion Detection	Embedded Corrosion Instrument (ECI)	Campbell Scientific	$1,300	Provides early warning of corrosion in reinforcement and is used as a health monitoring system	Reinforcement. One device per 100 ft^2
	Concrete Corrosion Sensors	ECI, www.vatechnologies.com	$1,200	Used to evaluate corrosion front progression	Readout device additional $7000
	Linear Polarization Resistance	Rohrback Cosasco Systems		Used to monitor corrosion rate and pitting tendancy	
	Electrical Impedance				
	Ultrasonic C-Scan	NTD Systems	$63,000	Used to locate corrosion in a structure	
		Silverwing			www.silverwignuk.com
Scour Monitoring/Measurment Devices	Magnetic Sliding Collar	ETI Instruments		Used in bridges as an integrated system	
	Float Out Device	ETI Instruments	$25000-$45000	Price includes spare parts and data acquisition/communication	http://24.89.186.109:8090/command=RTMC&screen=Main
	Sonar Scour Device	ETI Instruments	$75,000	Price includes spare parts and data acquisition/communication	
Crack Detection	Electrochemical Fatigue Sensing			Used in bridges to monitor fatigue cracks	
	Vibrating Wire Crackmeters	Slope Indicator	$350-$455	measures cracks in joints	Additional data aquistion of $500-$1300 or $9300 for complete package
		MATECH			
Tunnel Profile Monitoring System	Micro electro mechanical systems, accelerometers, digital bus	Slope Indicator		A series of fixed rods mounted to tunnel walls to monitor deformations	nts.com/PDFs/Tunnel%20Profile%20Monitoring%20Sys
		RST Instruments			
Weigh-in-Motion Systems	Piezo electric quartz	Kistler	$5000-$9000 per year per lane	Measure loads caused by traffic	er.com/IT_en-it/712_MeasuringPrinciple/Measuring-Prinz
Weather Stations		Kistler	$3,000	Monitor weather	
Multi-Depth Deflectometers	Series of LVDTs	Campbell Scientific	$20,000	Measurement of displacements at various pavement levels	http://www.dynatest.com/research-mdd.php;
		Dynatest			

Table 5.2: Typical costs of data acquisition systems

Description	Unit Price
Piezo-resistive Data Acquisition	$18,000
VW Multiplexers	$1,400
VW Signal conditioning	$500
Cell Modem	$1,200
Traffic Cabinet	$1,100
Power Conditioning	$1,000

Table 5.3: Costs of Web Based Data Viewing

Consultant Hosts Data (includes cell modem fees)	$125-250 per month
Cell Fees (typical if client provides service)	$50 per month
Hosting Software (if client wants to host data site)	$10,000 - $30,000

Table 5.4: Installation Fees Using Specified Sensors in Table 5.5

Task	Duration	Mobilization	Fee Range
Bridge Specified Inst.			
Deck Casting	1 week	3	$13,000
Beam Casting	2 days	4	$6,000
Final Install	1 week	5	$18,000
		Total	$37,000

Table 5.5: Typical instrumentation plan for a bridge

Gauge Type	**Unit Price**	**Quantity**	**Notes**
Strain- 1/4 Arm (includes completion unit)	$560	22	
Strain- VW	$150	22	
Weather	$1,400	1	Sensors
	$2,800	1	Tower (approximate- will change with location, height, tiedowns, etc.)
Tilt	$1,400	6	
Strain- 1/4 Arm	$560	7	
Cable	$0.82	5000	Assumes 150' per sensor

Chapter 6

IHM Testbed Host Project Identification and Evaluation

This chapter identifies urban freeway construction projects that could efficiently serve as hosts for an instrumentation testbed. These projects are critically evaluated and one project is identified and recommended as a candidate host.

6.1 Identification/Evaluation of Candidate Projects

Communications with WisDOT and discussion with a project panel identified the following current/future major transportation infrastructure construction projects:

1. I-94 North-South Freeway Project
2. Zoo Interchange Reconstruction Project
3. I-90/I-39 Expansion/Reconstruction Project
4. US-41 WI 441 Tri-County Freeway Project
5. Hoan Bridge Deck Reconstruction Project

The following is a critical evaluation for these projects:

I-94 North-South Freeway Project

The I-94 North-South corridor is a 35-mile segment from the Illinois state line to the Mitchell Interchange in Milwaukee County. This freeway reconstruction project will improve safety and help ease congestion of this important corridor. The pavement section consists primarily of a 12-in doweled Jointed Plain Concrete Pavement (JPCP) over a 3-in Hot Mix Asphalt (HMA) base layer. In the Mitchell Interchange portion of this project, a composite pavement is being constructed to include a 3.5-in HMA surface layer over an 11-in. doweled JPCP over a 3-in. hot mix asphalt (HMA) base layer. Instrumentation of these pavements will monitor the effects of traffic and environmental loads on critical pavement responses and will help determine the extent to which the HMA surface of the composite pavement helps reduce these critical concrete pavement responses. The construction schedule provides an opportunity to install instrumentation during the 2012 paving operations of the southbound lanes between Howard Avenue and the Mitchell Interchange.

The benefits of well-defined relationships between pavement/environmental loads and induced pavement stresses and strains will provide WisDOT with a scientific understanding of the relationships between design, construction, and environmental variables on the performance of

JPCP and composite pavement systems. Such an understanding will lead to larger benefits, such as enhanced design and performance of JPCP and composite pavement systems.

Zoo Interchange Reconstruction Project

The Zoo Interchange is currently the busiest interchange in the state and is scheduled for complete reconstruction beginning in 2013, with improvements to adjacent roadways in 2013-14 and complete reconstruction of the interchange in 2015-18. WisDOT recently announced a preferred alternative for the Zoo Interchange reconstruction and will submit a Final Environmental Impact Statement this summer. Final design will begin after the FHWA record of decision is released.

I-90/I-39 Expansion/Reconstruction Project

The I-39/90 corridor is a 45-mile segment from Beloit to Madison and is planned for upgrading to a 6-lane facility to improve safety and ease congestion. Soil studies are currently being conducted to aid in the structural design of the pavement facility. WisDOT is currently soliciting design consultants for this project. Construction for this project is scheduled to begin in 2015 and be completed in 2021.

US-41 WI 441 Tri-County Freeway Project

The new freeway reconstruction from County CB to Oneida Street in Winnebago County is a $360 million investment in highway infrastructure. Current and future traffic demands in the transportation corridor related to this project are significant. The project involves a 4-lane to 6-lane expansion of the roadway; a US-41/US-10/WIS-441 interchange super- and substructures; four service interchanges (County P, WIS-47, County AP, and Oneida St.); Little Lake Butte des Morts crossing super- and substructures, and auxiliary lanes between interchanges. The US-41 project team for WisDOT will manage the effort; the construction timeline extends from 2014 through 2019.

This freeway project has the potential to include many elements of smart infrastructure, as discussed earlier in this report. The interchange super- and substructures include opportunities for deck sensor technologies, strain sensor technology, and retaining wall tilt sensor technology to be implemented. The Little Lake Butte des Morts crossing affords the opportunity to include all the technologies present in the interchange structures, as well as tilt sensors for interior piers founded in the lake. The bridge superstructures are likely to be structural steel; therefore, there will be an opportunity to collect and monitor strain histories in the superstructure from the instant the project goes into service. There are pavement segments present in the construction corridor for implementing pavement sensors and for monitoring, as well. Overall, the construction corridor stretching from Coldspring Road to Oneida Street is an ideal candidate for a smart infrastructure corridor; however, the project's distant proximity to Milwaukee makes interaction with university personnel and resources in the southeast region more difficult.

Hoan Bridge Deck Reconstruction Project

The Hoan Bridge, constructed in 1972 and opened to full traffic service in 1998 with completion of the Lake Parkway, is slated to undergo deck reconstruction in the near future. While not the ideal candidate as a testbed for smart infrastructure, it offers the opportunity to implement and evaluate bridge deck chloride ingress sensor arrays. There are also opportunities to install strain sensors on the main superstructure girders to measure future strain ranges after the deck reconstruction is complete. For a larger and wider-scale smart infrastructure corridor application, the Hoan Bridge reconstruction is not the ideal choice because the superstructure has been in use for nearly a decade prior to strain gage installation, and there will be a decade of lost data before the smart infrastructure corridor is in place.

6.2 Recommendation of Testbed Host Project

Among the listed projects, the Zoo Interchange reconstruction project is recommended to host the infrastructure health monitoring testbed. The Zoo Interchange contains various components of critical transportation infrastructure components such as pavements, bridges, retaining walls, sign structures, slopes, and noise barrier. Infrastructure health monitoring plans for the Zoo Interchange will provide WisDOT with significant data and information and benefits, as presented earlier in this report, since this interchange is the most used system in the state in terms of traffic volume and load. Moreover, the location of the Zoo Interchange within the greater Milwaukee area provides an advantage for IHM testbed in terms of data communication and transmission. A testbed at the Zoo Interchange is within close proximity of sources needed to power and transmit collected data, including the WisDOT State Traffic Operations Center (STOC) fiber optic network. This will enable WisDOT to use the existing Intelligent Transportation Systems (ITS) communications infrastructure for transport of data to the STOC or other identified locations, including research institutions.

In addition, construction of the Zoo Interchange has not started yet, giving WisDOT the time to implement/contract the testbed plans. Figures 6.1 and 6.2 present a map for the Zoo Interchange project, with locations of various infrastructure components. The core of the Zoo Interchange, presented in Figure 2, is recommended to host the testbed. Pavement test sections, bridge and bridge substructure components, and retaining walls can be selected within the core of the project for implementing the presented instrumentation plans.

The research team also recommends implementing a health monitoring instrumentation plan for the composite pavement on the I-94 North-South Freeway. This type of pavement is considered a new concept in Wisconsin, with no history or performance or data available. Such implementation will provide WisDOT and the research community with valuable data and information on pavement performance that can help in future designs of similar pavements and in maintaining operations.

Figure 6.1: Proposed transportation infrastructure (pavement, bridges, and retaining walls) for the Zoo Interchange

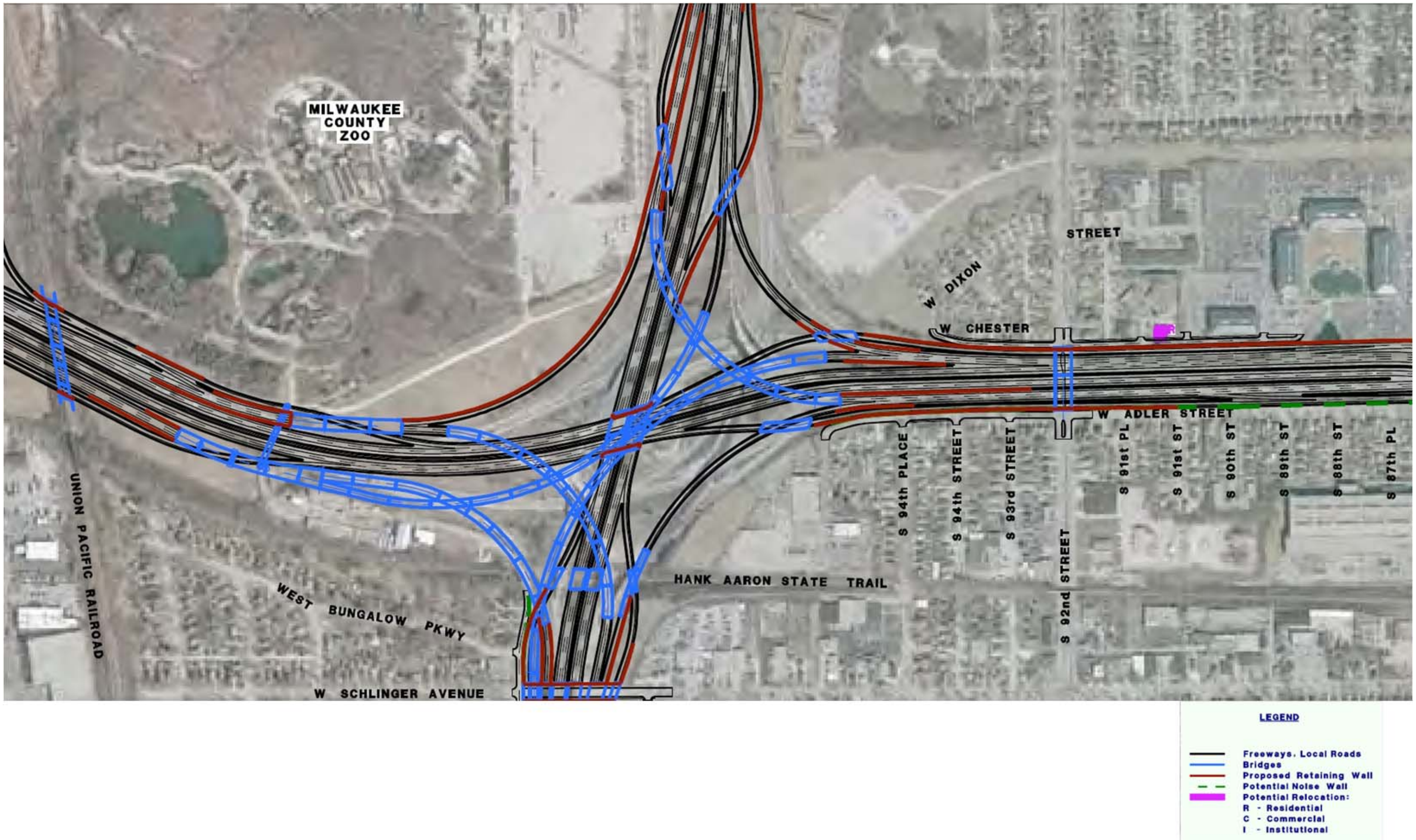


Figure 6.2: The core of the Zoo Interchange is recommended to host the instrumentation testbed

Chapter 7

Infrastructure Health Monitoring Plan for Zoo Interchange

This chapter presents a comprehensive field instrumentation plan for the transportation infrastructure at the Zoo interchange. The plan identifies structures to be monitored, recommends sensors/devices and installation locations, and presents a cost analysis.

7.1 Planning for Instrumentation

In order to identify data elements to be collected from structures, objectives for the structure heath monitoring program need to be identified in the context of design, construction, and maintenance. Dunnicliff (1993) presented the following steps for effective planning the field instrumentation of geotechnical structures; however, these steps are modified slightly in order to apply not only to geotechnical structures, but also to bridges, pavements, and sign structures:

1. Define conditions of the project, such as project type, project layout, status of nearby structures or other facilities, environmental conditions, planned construction method, and knowledge of crisis situation.

2. Predict mechanisms that control behavior.

3. Define the questions that need to be answered: determine the data elements to collect and how the collected data will help answer questions.

4. Define the purpose of the instrumentation such as benefits during design phase, benefits during construction (e.g., safety, construction control, enhancing the state of the art, verifying satisfactory performance after construction is complete).

5. Select the parameters to be monitored: strains, forces, displacements, corrosion activity, vibrations, pore water pressure or joint water pressure, total stress within soil mass, total stress at contact with structure or rock, stress within rock mass, tilt, strain in soil or rock, load or strain in structural members, cracking and temperature.

6. Predict magnitudes of change: predict maximum value (instrument range), predict minimum value (instrument sensitivity or accuracy), and determine hazard warning levels.

7. Devise remedial action: devise action for each hazard warning level (ensuring that labor and materials will be available), determine who will have contractual authority for initiating remedial action, ensure that the communication channel is open between design

and construction personnel, and determine how all parties will be forewarned of planned remedial actions.

8. Assign tasks for design, construction, and operation phases: complete Table 7.1; assign supervisory responsibility for tasks by instrumentation specialist, identify liaison and reporting channels; identify who has overall responsibility and contractual authority for implementation.

9. Select instruments: plan for high reliability (e.g., maximum simplicity, don't allow lowest cost to dominate selection; maximum durability in installed environment; minimum sensitivity to climatic conditions; good past performance record; consider transducer, readout unit, and communication system separately; is reading necessarily correct? can calibration be verified after installation?); discuss application with manufacturer, recognize any limitations in skill or quantity of available personnel; consider both construction and long-term needs and conditions; ensure good conformance, ensure minimum interference to construction and minimum access difficulties; determine need for data acquisition system type; plan for spare parts and standby readout units; evaluate adequacy of lead time; evaluate adequacy of time available for installation; question whether the selected instrument will achieve the objective.

10. Select instrument locations: identify zones of primary concern, select primary instrumented sections, select secondary instrumented sections, plan quantities to account for less than 100% survival, arrange locations to provide early data, arrange locations to provide cross-checks, avoid nonconformance or weakness at clusters.

11. Plan to record factors that may influence measured data: construction details, construction progress, visual observations of expected and unusual behavior, hidden conditions, and environmental factors.

12. Establish procedures for ensuring correctness: visual observations, duplicate instruments, backup system, study of consistency, study of repeatability, regular in-place checks.

13. List the specific purpose of each instrument.

14. Prepare budget. Include costs, being particularly careful to make a realistic estimate of project duration for: planning monitoring program, making detailed instrument designs, procuring instruments, making factory calibrations, installing instruments, maintaining and calibrating instruments on a regular schedule, establishing and updating data collection schedule, collecting data, processing and presenting data, interpreting and reporting data, deciding on implementation of results.

15. Write instrument procurement specifications: assign responsibility for procurement (e.g., construction contractor, owner, design consultant, instrument suppliers acting as assigned subcontractors), select specifying method (e.g., descriptive specification, with brand name and model number; descriptive specification, without brand name and model

number, performance specification; select basis for determining price: negotiation, bid), write specifications, plan factory calibrations, plan acceptance tests when instruments are first received by user, and determine responsibility.

16. Plan installation: prepare step-by-step installation procedure well in advance of scheduled installation dates, including list of required materials and tools; prepare installation record sheets; plan staff training; coordinate plans with contractor; plan access needs; plan protection from damage and vandalism; plan installation schedule.

17. Plan regular calibration and maintenance: plan calibrations during service life, plan maintenance.

18. Plan data collection, processing, presentation, interpretation, reporting, and implementation:

    a. Plan data collection (prepare preliminary detailed procedures for collection of initial and subsequent data, prepare field data sheets, plan staff training, plan data collection schedule, plan access needs).
    b. Plan data processing and presentation (determine need for automatic data processing, prepare preliminary detailed procedures for data processing and presentation, prepare calculation sheets, plan data plot format and plan staff training)
    c. Plan data interpretation (prepare preliminary detailed procedures for data interpretation).
    d. Plan reporting of conclusions (define reporting requirements, contents, and frequency)
    e. Plan implementation

19. Write contractual arrangements for field instrumentation services: select field service contract method, write detailed specifications.

20. Update budget (include costs for all tasks listed in step14).

Table 7.1: Example of task assignment for owner-instigated monitoring program (after Dunnicliff 1993, modified)

Task	**Responsible Party**				
	Owner	**Research & Development Community**	**Design Consultant**	**Instrumentation Specialist**	**Construction Contractor**
Plan monitoring program	X	X	X	X	
Procure instruments and make factory calibrations			X	X	
Install instruments				X	X
Maintain and calibrate instruments on regular schedule				X	X
Establish and update data collection schedule		X	X	X	
Collect data	X	X		X	
Process and present data		X		X	
Interpret and report data		X	X	X	
Decide on implementation of results	X		X		

7.2 Instrumentation Plan for Pavements

Pavement Monitoring Objectives: The primary focus of a pavement monitoring plan is to document the effects of environmental and load-induced stresses, strains and deflections within the pavement structure; therefore, direct measurements of traffic loadings and environmental conditions are combined with pavement structural responses to assess fatigue consumption and ultimately assess the impact on pavement performance.

Pavement instrumentation necessary to assess structural performance can be generally grouped into three main categories: traffic loadings, environmental measurements, and pavement responses.

The following pavement structure components are important for implementing a health plan:

1. Asphalt Concrete (AC) pavement surface layer
2. Portland Cement Concrete (PCC) pavement surface layers (slab)
3. Base course and subbase layers
4. Subgrade soil
5. PCC pavement joint
6. PCC pavement dowel bars

Pavement structure data elements significant to health monitoring:

1. Stress
2. Strain
3. Deflection
4. Atmospheric data (moisture, humidity, wind speed, precipitation, solar radiation)
5. Environmental conditions within pavement structure (temperature, moisture)
6. Environmental conditions in subgrade (temperature, moisture)

7.2.1 Traffic Loadings

Quantification of traffic loadings must consider the travel speed, magnitude and geometry of wheel loads, and the location of the loadings within the travel lane(s). Installation of Weigh-In-Motion (WIM) and wheel wander systems are necessary to quantify the speed, intensity, and placement of moving wheel loads.

The WIM system directly measures wheel loads and influence times for passing vehicles. Based on this information, algorithms are used to compute axle loads, axle spacings, gross vehicle weight, travel speed, and vehicle classification. At a minimum the WIM system should conform to ASTM Type I requirements, which specify tolerances for measurements of $\pm$25% for individual wheel loads, $\pm$20% for axle loads, $\pm$15% for axle load groups and $\pm$10% for gross vehicle weight. For ease of installation and to minimize operating costs, it is recommended that quartz piezoelectric sensors be used for wheel load measurements, installed as surface-mounted strips oriented perpendicular to traffic flow within each wheel path. These sensors have been successfully used at the MnROAD test facility (MnROAD, 2009) and within the North Leg of the Marquette Interchange project (Hornyak, et al., 2007). The WIM strips are paired with an inductive loop, typically positioned upstream of the piezoelectric sensors, to detect vehicles and provide data necessary to compute vehicle length. The inductive loop can also be used to alert the WIM system of an approaching vehicle.

Lateral placement of wheel loadings have a direct impact on the load induced deflections and stresses in the pavement structure. Measuring wheel placement requires a minimum of three surface-mounted piezoelectric strips installed, with two perpendicular to traffic flow and one at an angle to the perpendicular strips, resulting in an "N" configuration. For better resolution of single- and dual-wheel loads, two angled strips are used, resulting in an "M" configuration. It may be possible to use one or more of the piezoelectric sensors of the WIM system as part of this lateral placement measurement system. Figures 7.1 and 7.2 provide a schematic illustration of the inductive loop, wheel wander ("M" configuration) and WIM strips. Figure 7.3 provides a schematic illustration of the WIM/Wander setup successfully used on the North Leg of the Marquette Interchange project.

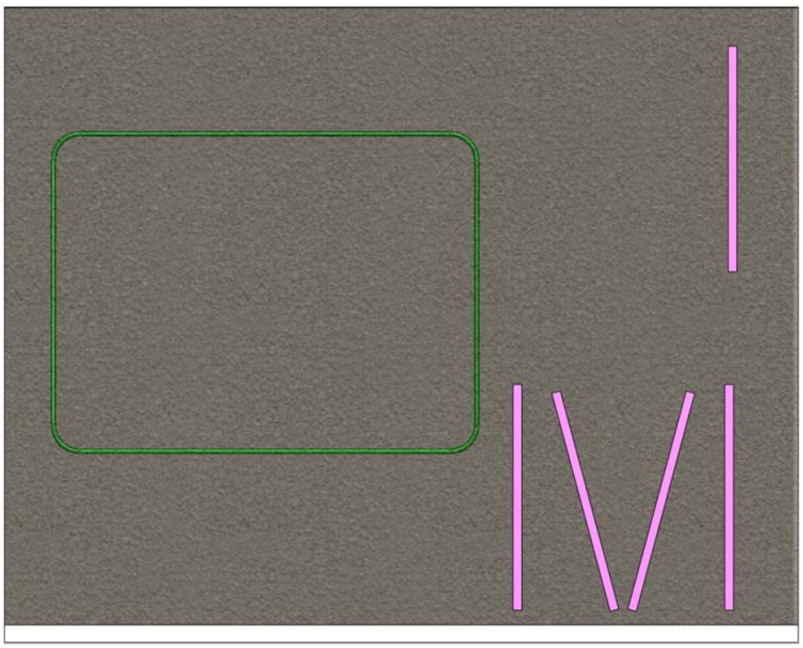


Figure 7.1: Schematic layout of inductive loop, wander and WIM strips

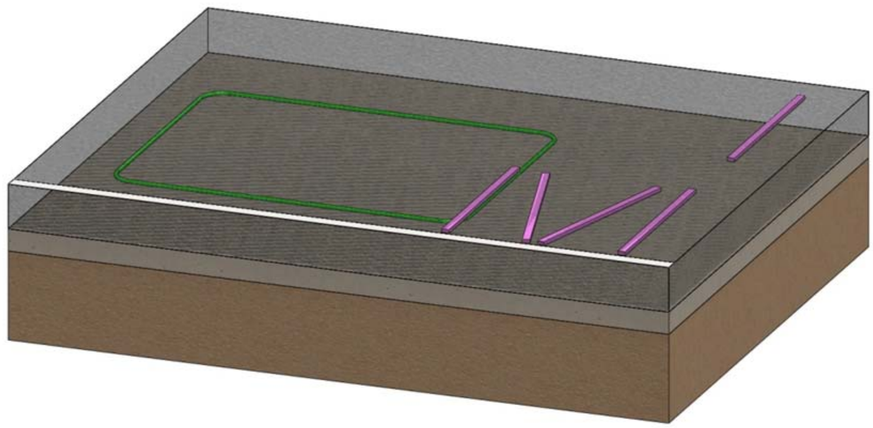


Figure 7.2: Schematic positioning of inductive loop, wander and WIM strips

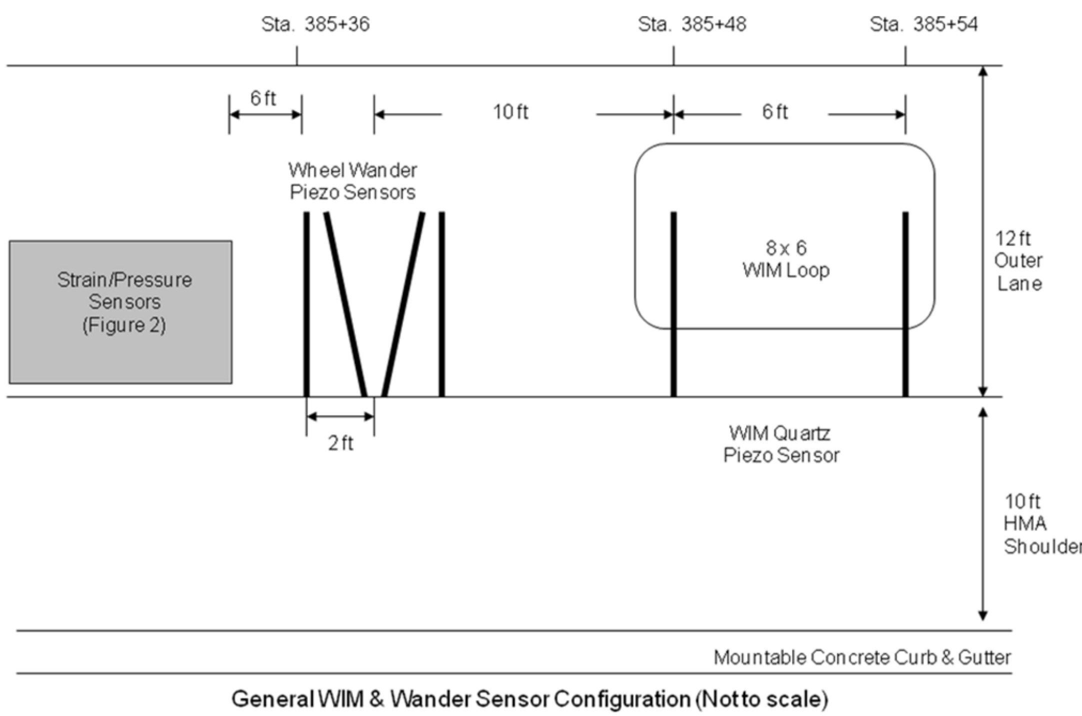


Figure 7.3: Schematic positioning of WIM/wander strips – North Leg Marquette Interchange

7.2.2 Environmental Measurements

Environmental measurements typically include local atmospheric measurements in the vicinity of the pavement instrumentation and within-pavement measurements of moisture and temperature. Local atmospheric measurements of interest include air temperature, relative humidity, wind speed, precipitation, and intensity of solar radiation. All of these measures are typically integrated within a conventional weather station mounted alongside the roadway. Multi-depth temperature and moisture measurements should be obtained within the surface layer(s), base and subgrade materials. Temperature measurements within the surface layer(s) can be obtained at incremental depths of one to two inches, providing sufficient data to characterize temperature gradients within the layer(s). Temperature and moisture measurements within the base layer(s) should be obtained at approximately mid-depth. Temperature and moisture measurements within the subgrade layer should be obtained at approximately 1- to 2-ft intervals to a depth of at least 2-ft below the expected depth of frost penetration.

For jointed concrete and composite pavement structures, short-term variations of through-slab temperature/moisture gradients can generate slab curling/warping and significant stresses. Longer-term changes in slab temperatures can result in openings and closings of the transverse contraction joints. The effects of through-slab temperature/moisture gradients can be measured with tilt-meters, Linear Variable Differential Transducers (LVDTs), relative humidity sensors, and interface pressure cells. Tilt-meters were successfully used at the MnROAD facility (Koubaa and Stolarski, 2002) to monitor slab curling and warping due to temperature and moisture gradients, respectively. Figures 7.4 and 7.5 provide photos of these devices.

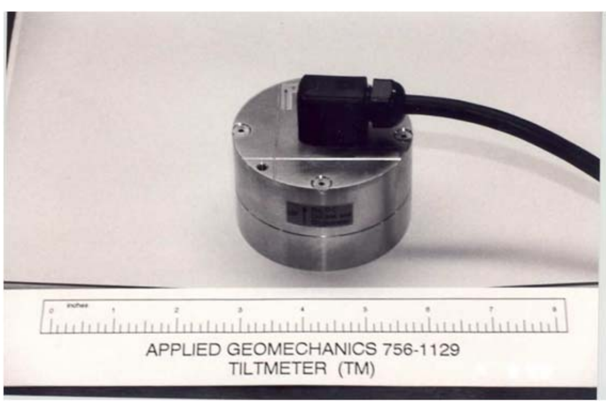


Figure 7.4: Applied geomechanics tiltmeter

Figure 7.5: Tiltmeter installations at MnROAD

Imbedded LVDTs were also used at the MnROAD facility (Koubaa and Stolarski, 2002) to measure vertical deflections in response to slab curling/warping. Figures 7.6 and 7.7 provide photos of these devices.

Figure 7.6: Schaevitz LVDT and mounting ring

Figure 7.7: LVDT installed at MnROAD

Custom-made relative humidity sensors were used with limited success at the MnROAD facility. Figure 7.8 provides an installation photo from the MnROAD project.

Figure 7.8: Relative humidity "Trees" installed at MnROAD

Interface pressure cells, positioned at the bottom of the PCC slab, are proposed to detect changes in vertical contact pressures due to slab curling/warping. In concept, as the slab curls/warps, portions of the slab may become unsupported by the foundation with resulting interface pressures tending towards zero.

Joint opening/closing due to longer-term temperature changes were successfully monitored at the MnROAD facility with pie-shaped displacement transducers. Figures 7.9 and 7.10 provide photos of the Tokyo Sokki devices and mounting clips used at MnROAD, respectively.

Figure 7.9: Tokyo Sokki joint opening gauge

Figure 7.10: Core mounting used at MnROAD

To monitor the effects of slab response to environmental changes, it is proposed that slab measurements with imbedded LVDTs and interface pressure cells be taken at a minimum of six locations, including the geometric center, near two slab corners, and at three mid-panel locations near the transverse and longitudinal joints. These positions are illustrated in Figure 7.11.

Moisture and temperature gradients should be obtained at a minimum of two locations, including the geometric center and near one slab corner location. Tilt-meter measurements should be obtained at a minimum of three locations, including near one slab corner and mid-panel locations adjacent to a longitudinal and transverse joint. For comparison, installation layouts used at MnROAD for various test cells are illustrated in Figures 7.12 and 7.13.

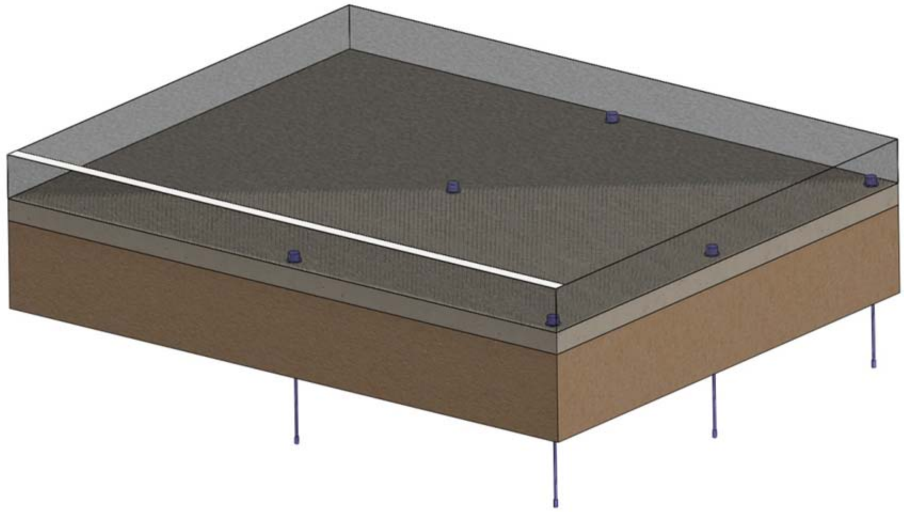


Figure 7.11: Mounting locations for LVDTs and pressure cells

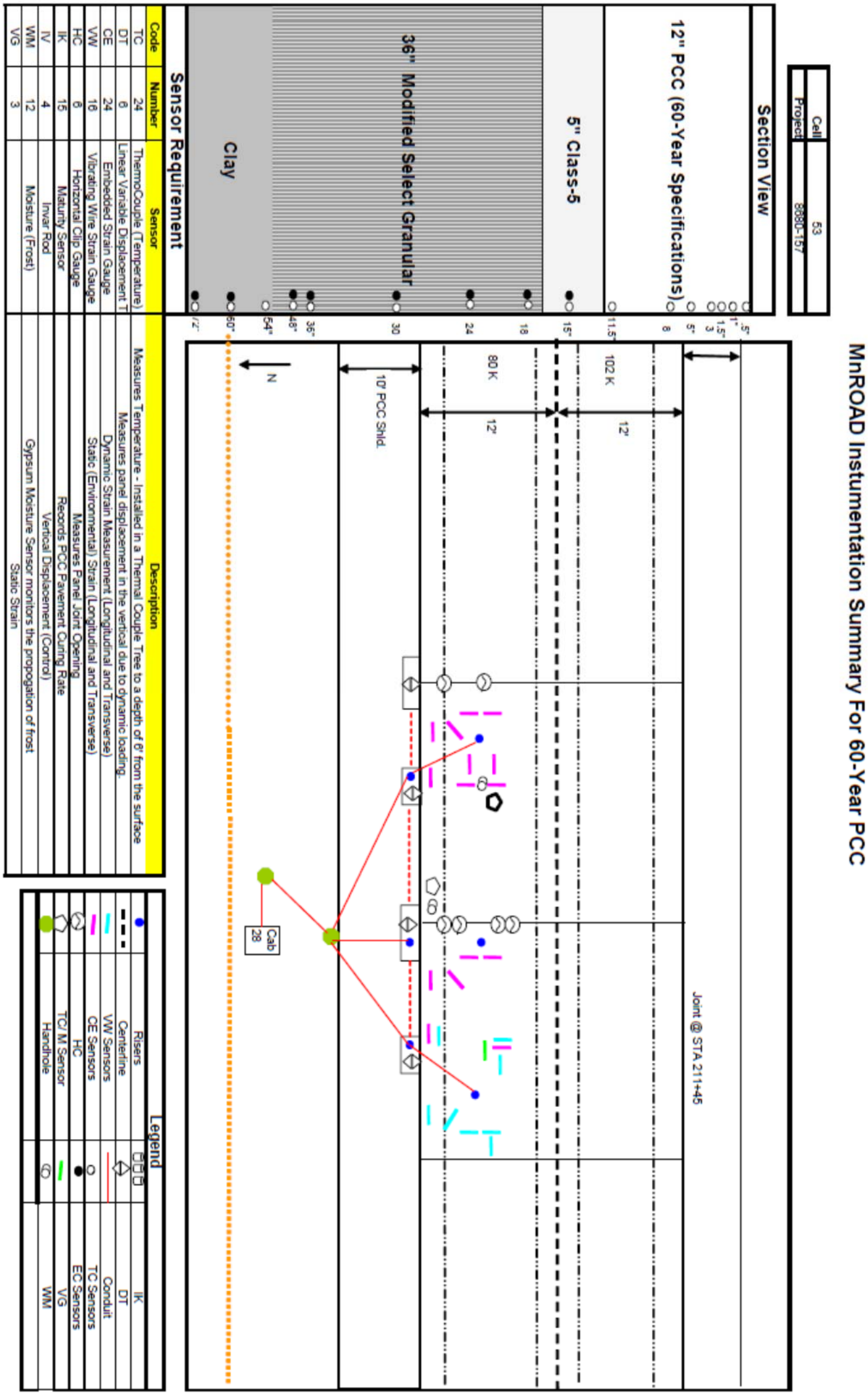


Figure 7.12: MnROAD instrumentation for cell 53

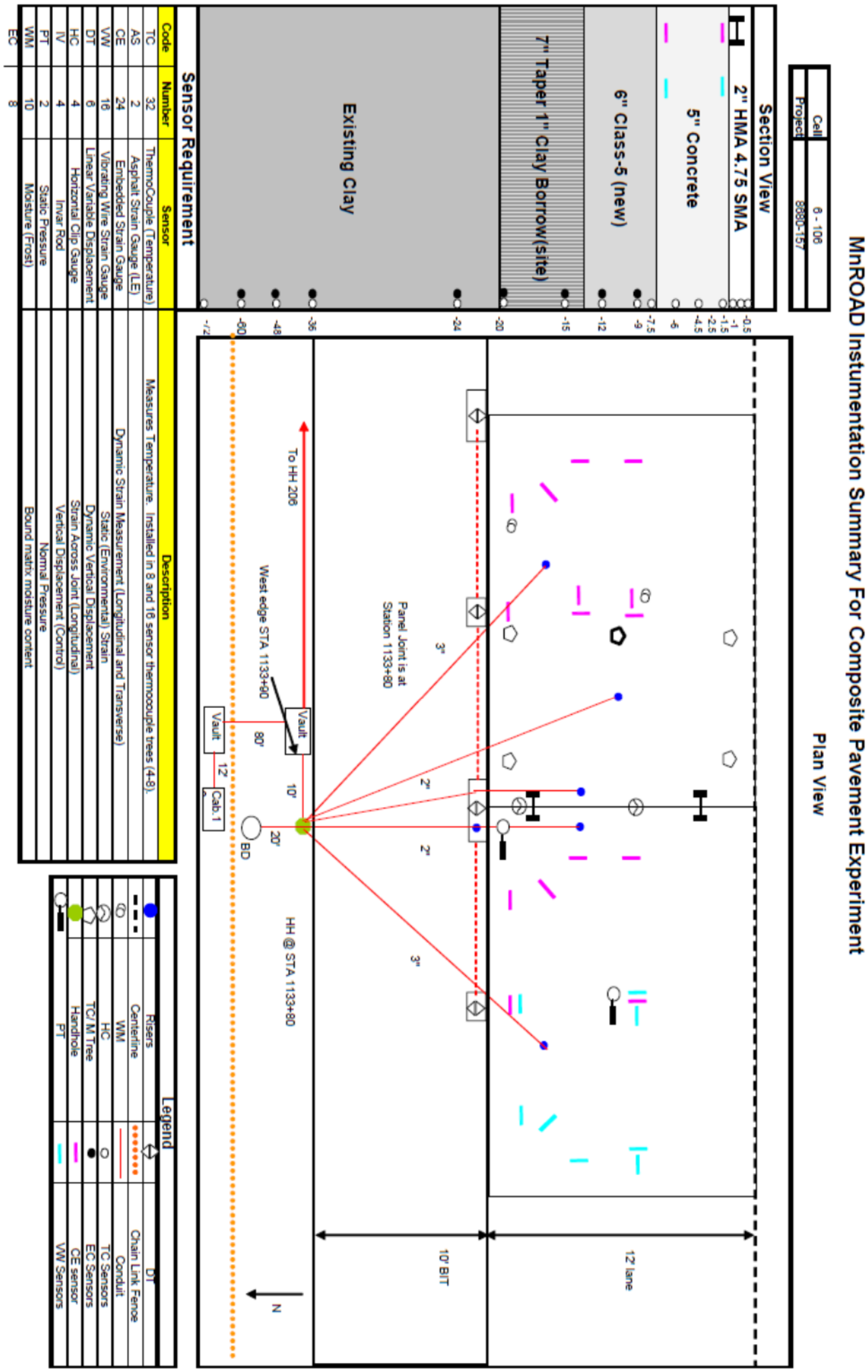


Figure 7.13: MnROAD instrumentation for cell 106

7.2.3 Pavement Response Measures

Pavement response measures include dynamic strains, pressures and deflections produced by each moving wheel load. Strain response due to dynamic traffic loads are typically measured with electrical resistance strain gages imbedded within an H-shape anchor. Figures 7.14 – 7.17 provide illustrations of various strain gages used at MnROAD and the North Leg of the Marquette Interchange project.

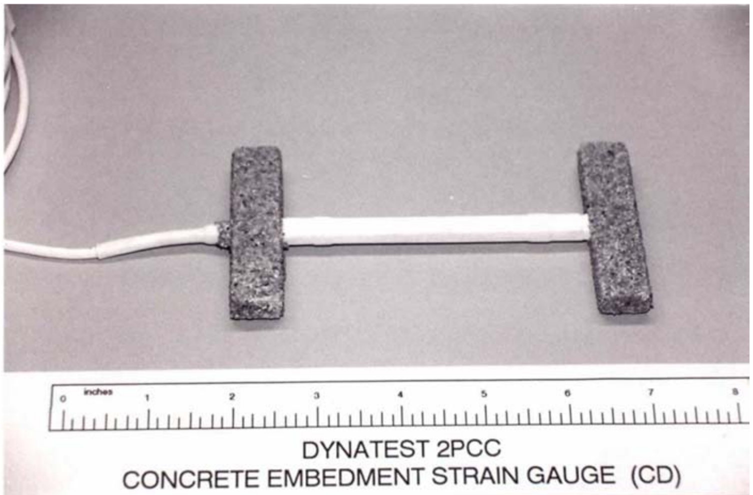


Figure 7.14: Dynatest embedment strain gage

Figure 7.15: MnROAD strain gage setup

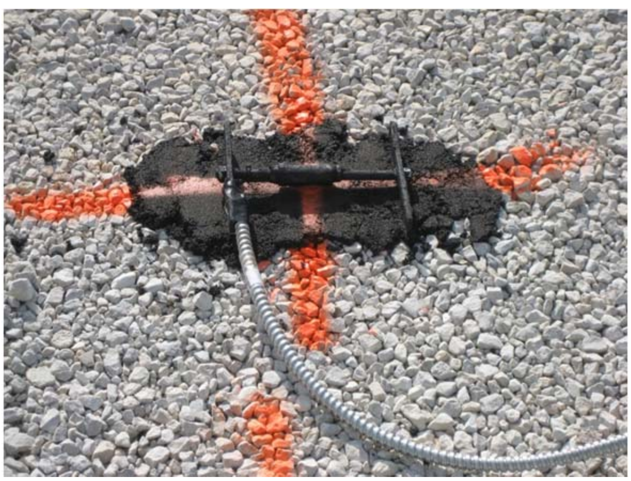


Figure 7.17: Marquette strain gage arrays

Figure 7.16: CTL embedment strain gage

Strains sensors are deployed at critical locations within the pavement structure to capture the influence of moving wheel loads. For HMA pavements, horizontal strains are typically measured at the bottom of one or more of the HMA layers in both the transverse and longitudinal directions. Sensors are spread out within the wheel path to capture the effect of wheel wander. Figure 7.18 provides a schematic illustration of a one-layer sensor array. Figure 7.19 illustrates the arrays used within the North Leg of the Marquette Interchange.

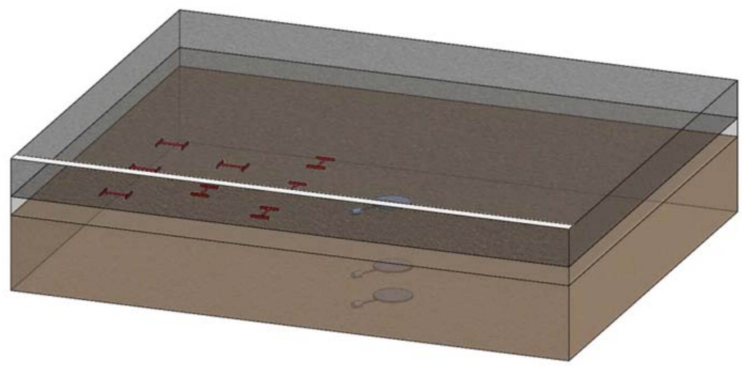


Figure 7.18: Schematic layout of a one-layer sensor array for HMA pavements

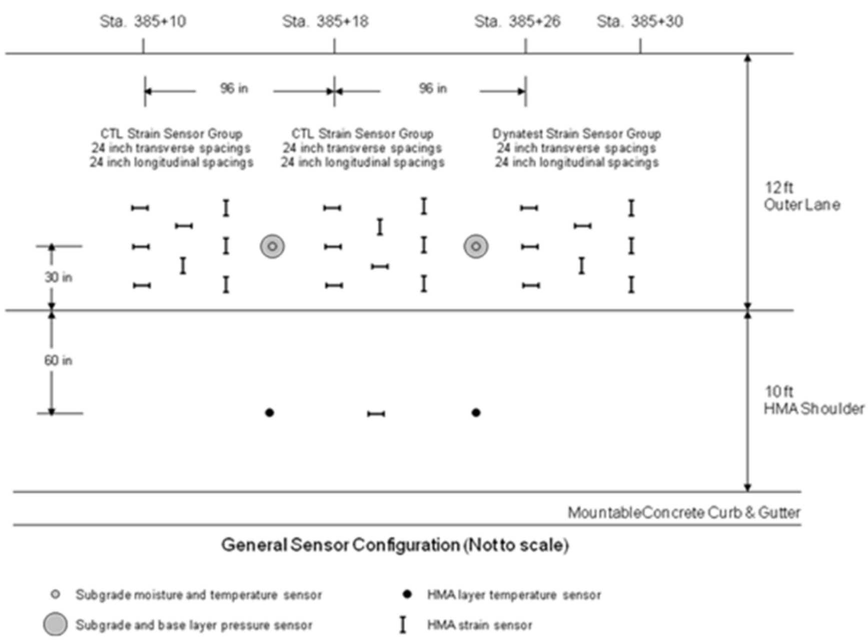


Figure 7.19: Schematic layout of sensor arrays for the Marquette Interchange

For PCC and Composite pavements, horizontal strains are typically measured at near top and bottom of the PCC layer and at the bottom the HMA layer. PCC sensors are typically located at critical edge locations, as shown in Figure 7.20, or distributed at edge and corner locations, as shown in Figures 7.12 and 7.13.

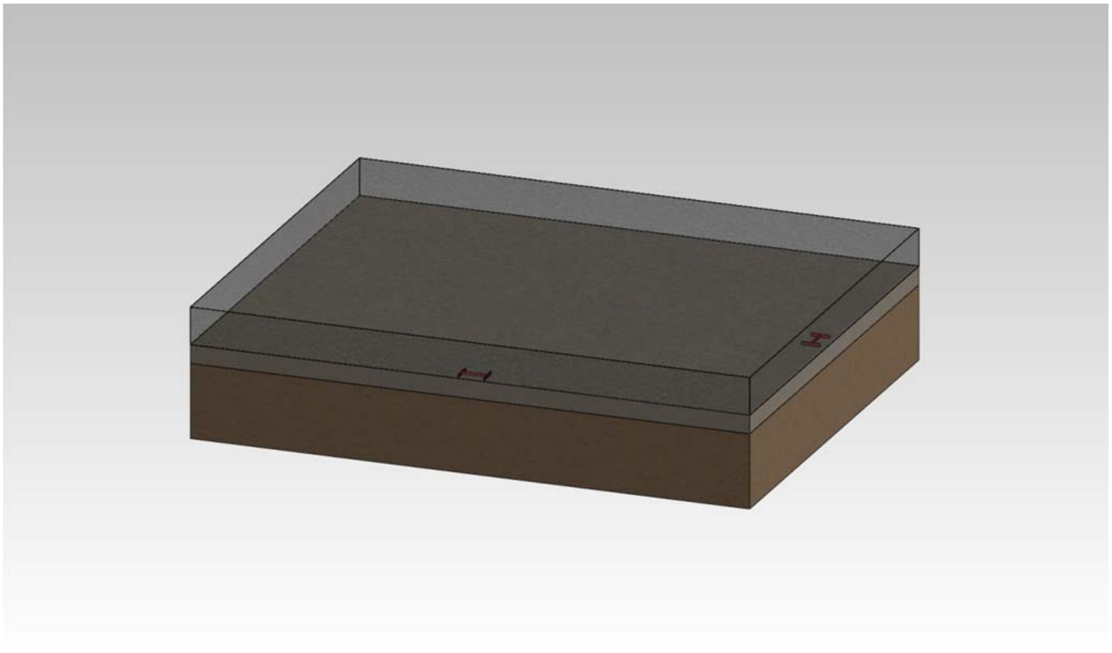


Figure 7.20: Critical edge locations for PCC slabs

Dynamic deflections within PCC pavements can be measured with the same LVDTs imbedded for measurement of slab curling/warping (See Figure 7.11). The influence of moving loads on the vertical pressures within the pavement structure can be monitored with earth pressure plates. These plates, which were successfully used within the North Leg of the Marquette Interchange project, are illustrated in Figure 7.21.

Figure 7.21: Geokon earth pressure cells

7.3 Instrumentation Plan for Bridge Structures

There are many potential structures that can be monitored in the smart infrastructure corridor selected. The entire corridor and maintenance needs within that corridor need to be established a-priori in order to establish the greatest gain with finite resources that are available. The objectives of this section are to highlight typical components of the infrastructure corridor that can be instrumented, the objectives of the instrumentation, the type and location of instruments that can be used in the instrumentation array, the time of installation of these instruments in the construction cycle, the data acquisition system components that are needed, and the typical flow of data from system monitored to final storage or display.

Designing bridge structural systems involves many assumptions regarding loading magnitude, loading distribution, and structural system load transfer mechanisms, which can rarely be validated on in-place structures. As a result, one must always keep in mind that a smart infrastructure component can be used as a device to validate all assumptions built into structural system design, and validation of these assumptions improves the design process. Therefore, the smart infrastructure component should also be used as a tool for developing design procedures that lead to more economical systems through greater and better understanding at design time.

The following bridge components are considered:

1. Bridge decks
2. Bridge girders (precast concrete, structural steel tub, and structural steel plate girders)
3. Expansion joints
4. Bearings
5. Bridge abutments
6. Bridge piers
7. Piles

The following bridge data elements are identified:

1. Strains (internal and external)
2. Forces (internal and external)
3. Displacements
4. Vibrations
5. Cracking (loading and fatigue)
6. Corrosion
7. Chemical attack

7.3.1 Typical Bridge Super- and Sub-Structures

The first component in a potential smart infrastructure corridor to be considered is a typical two-span precast concrete girder with Cast-In-Place (CIP) deck bridge superstructure with typical bench-type abutments and interior hammerhead pier. This super and substructure type is ubiquitous in the Wisconsin transportation network and will likely be contained in any corridor considered for use as a SMART infrastructure system. This section outlines the instrumentation objectives, the instrumentation array and instrumentation types, and the data flow and storage issues.

In situations where structural steel girders (tub or I-shaped) and cast-in-place concrete deck superstructures are present, the instrumentation objectives, instrumentation array, and the sensors selected are substantially similar; therefore, this section focuses on precast girder and cast-in-place deck superstructure systems.

7.3.2 Instrumentation Objectives

It is very easy to over-instrument a system, which generates information overload and causes data synthesis difficulties. The objectives of the instrumentation for a typical precast concrete girder with CIP deck superstructure and substructure is highlighted in this section prior to a detailed discussion of the instrumentation array and data storage and flow issues. The typical precast girder and CIP deck superstructure system with corresponding CIP substructure have several needs with regard to monitoring health and establishing warning signs of early deterioration. Such needs and objectives of the instrumentation array are outlined, as follows.

If a steel girder superstructure system is present, instrumentation objectives related to structural steel fatigue at critical detail locations will also be present.

Longitudinal Deck Strain:

There has been concerns expressed recently that CIP bridge decks are cracking prematurely and that this premature cracking can cause premature deterioration of CIP bridge decks. Wan, et al. (2010) recently completed a research effort indicating that strains accumulated very early after deck placement may be sufficient to cause cracking in CIP bridge decks before traffic loading is applied. Furthermore, longitudinal deck strains can also give insight and confirmation of load transfer mechanisms in the longitudinal direction and changes in these transfer mechanisms, thereby leading to indicators of premature superstructure deterioration.

The longitudinal strains in the bridge deck quantify the extent to which continuity is present in the superstructure. More specifically, the precast concrete girders in the system rely upon longitudinal continuity reinforcement present in the CIP bridge deck to generate the live load resistance continuity conditions necessary for the superstructure to carry loading as intended to the substructure. Longitudinal strains also can measure the magnitude and distribution of temperature-, shrinkage-, and creep-induced strains in the bridge deck in the longitudinal direction, as well as the distribution of these strains in the transverse direction.

The longitudinal deck strain should be monitored in the CIP bridge deck at locations above the interior pier. Furthermore, these strains should be measured in multiple locations in the transverse direction to monitor gradient in strain in this direction. As a result, these strains will give a measure of longitudinal-direction continuity present in the superstructure system and changes in this load transfer mechanism with time. These strains will also give a measure of lane loading distribution in the transverse direction over the interior pier, thereby quantifying this essential load transfer mechanism and changing it with time.

The longitudinal deck strains should be monitored through the construction cycle (i.e. immediately after deck placement) so that accumulated shrinkage-, temperature-, and creep-induced strains can be captured. If this monitoring is conducted at time of deck placement and continuously thereafter, much greater understanding of these strains and their contribution to premature deck cracking will be gained. Furthermore, understanding the magnitude of these deck strains and their accumulation with time will indicate the width of cracks in the bridge deck, thereby triggering epoxy injection maintenance procedures.

Longitudinal strains in the bridge deck can be monitored using strain gaging the continuity of steel reinforcement in the superstructure. It should be noted that both instantaneous (dynamic) and long-term strains should be monitored.

Transverse Deck Strain:

Transverse strains in the bridge deck give important insight into the load transfer mechanisms present in the deck and changes in these load transfer mechanisms with time, giving warning signs of distress. These deck strains also allow the construction cycle to be monitored and more specifically, long-term strains in the deck to be evaluated to quantify the effects of shrinkage, creep, and temperature. Finally, monitoring transverse deck strain allows design models to be evaluated, providing greater understanding of deck load transfer mechanisms.

Transverse strains through the thickness of the bridge deck can be monitored using strain gaging at top- and bottom-reinforcing steel mat locations. It should be noted that both instantaneous (dynamic) and long-term strains should be monitored.

Deck Surface Conditions:

The surface conditions on the bridge deck, along with weather monitoring, can help determine the impact of environmental conditions on the strains and resulting stresses in the bridge deck. For example, if there is standing water or ice on the bridge deck, the cooling/warming strains generated in the bridge deck can be monitored, providing better understanding and actual quantification of the strain cycling and strain magnitudes generated during environmental changes. Furthermore, the surface conditions present on the bridge deck can be used to correlate with the accumulation of de-icing chemicals in the bridge deck with time. The environmental conditions that should be monitored are deck surface temperature water film levels present, and deck surface conditions (dry/damp/wet/ice).

Chloride Penetration Into Deck:

It has long been known that the penetration of de-icing chemicals into the concrete composing the bridge deck contributes to the early deterioration of bridge decks. The extent to which these deicing chemicals migrate into the bridge deck and concentrate must be measured to assess the long-term performance of bridge decks and to track deterioration over time.

Embedded corrosion instruments placed at strategic locations throughout the bridge deck at various levels can provide information related to the concentration and depth to which deicing chemicals have penetrated the concrete bridge deck. This will give some indication of the extent to which the concrete has been compromised and the likelihood of corrosion progression in the reinforcing steel. It is understood that epoxy coating is present on reinforcing steel, but research has indicated that the epoxy coating can be compromised and it is not as effective as anticipated.

Deck Interior Temperature:

The interior temperature variation and distribution within the bridge deck can help to understand and quantify heat of hydration and temperature-induced strains, and their effects on deterioration in the bridge deck. These temperatures can and should be tracked during construction, and long-term monitoring during the bridge deck's service life should be tracked. Gradients of temperature through the bridge deck will also help quantify thermally induced strains that cause cracking within the bridge deck. It should be noted that having bridge deck temperature gradients along with internal deck strains makes a long-term monitoring program very effective because temperature-induced strains are relatively poorly understood in bridge engineering.

Wind and Temperature:

The environmental conditions in the vicinity of a bridge are very important to understanding the magnitude of environmentally induced mechanics on a bridge. The most effective way to monitor this is to place a weather monitoring station in proximity to the smart infrastructure corridor. Correlation with environmental conditions with those seen in the deck superstructure components is of a primary concern.

It should be noted that Automated Surface Observation System (ASOS) sites can be in relative proximity of instrumented infrastructure components, and these ASOS sites can be used to gather wind speed, wind direction, and other weather-related data. It should be noted, however, that local conditions can vary significantly from the conditions at an ASOS site (Foley, et al. 2011) and use of these sites to quantify local weather information should be carefully qualified.

Substructure Tilt:

The tilt of interior piers and abutments can give indication of substructure and superstructure distress. Tilt of an interior bridge pier within a stream or river can indicate substructure compromise through scour. Substructure tilt will likely not be a concern for long-term health monitoring; it can be used to assess potential distress at joints at the ends of the bridge deck.

7.3.3 Instrumentation Array

The typical precast bridge super- and sub-structure includes several components for which monitoring can help assess health and in-service performance. Figures 7.22 and 7.23 illustrate a typical two-span precast concrete girder, cast-in-place bridge superstructure and a potential instrumentation layout for health monitoring. This two-span bridge super- and sub-structure configuration is ubiquitous in the transportation network in Wisconsin.

As outlined earlier in this section, the instrumentation array for a superstructure system involving structural steel tub girders or structural steel I-shaped plate girders is substantially similar. The main difference is the need to include strain sensors in suitable locations in order to understand the fatigue performance of the superstructure through monitoring stress ranges present in the superstructure at critical locations.

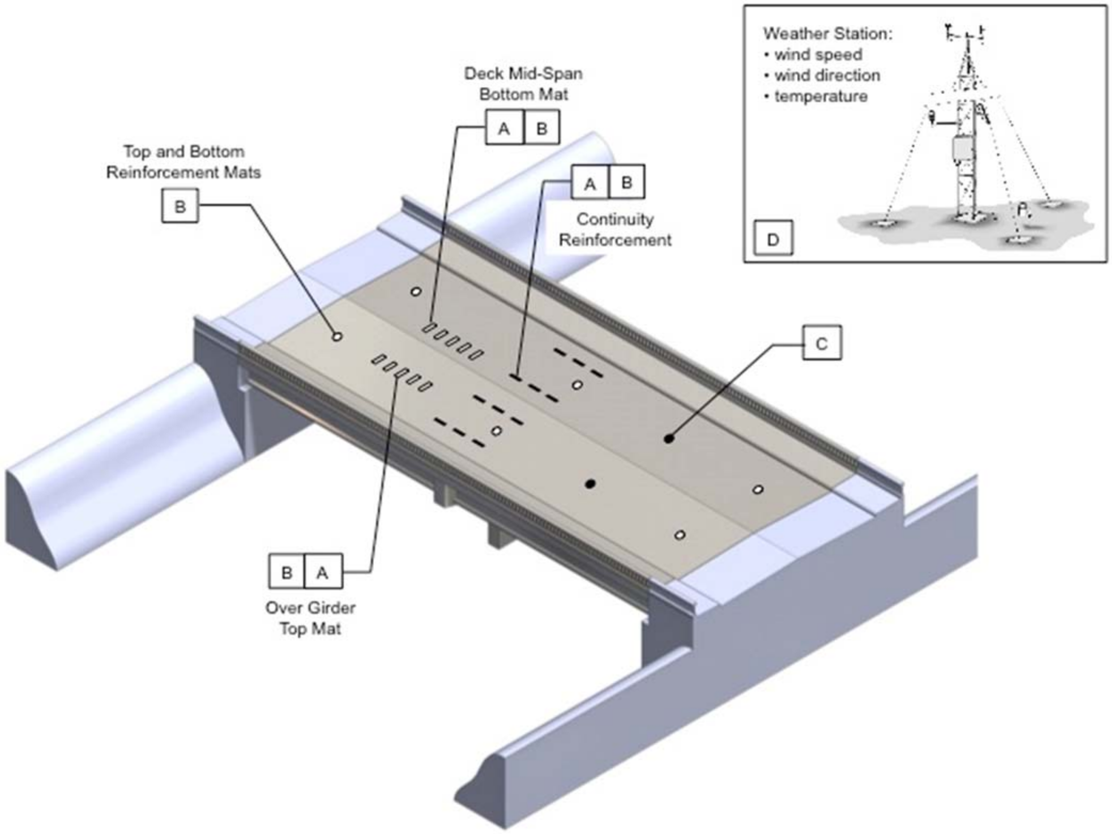


Figure 7.22: Precast concrete bridge instrument layout top isometric

The instrumentation in Figures 7.22 and 7.23 are denoted using the alphanumeric labels. Each sensor label correlates with a specific sensor type in Table 7.2. Table 7.2 and Figures 7.22 and 7.23 can be used in concert with one another to understand sensor layout, sensor number, sensor location, instrument type, and placement within the construction sequence for this component in the smart infrastructure corridor.

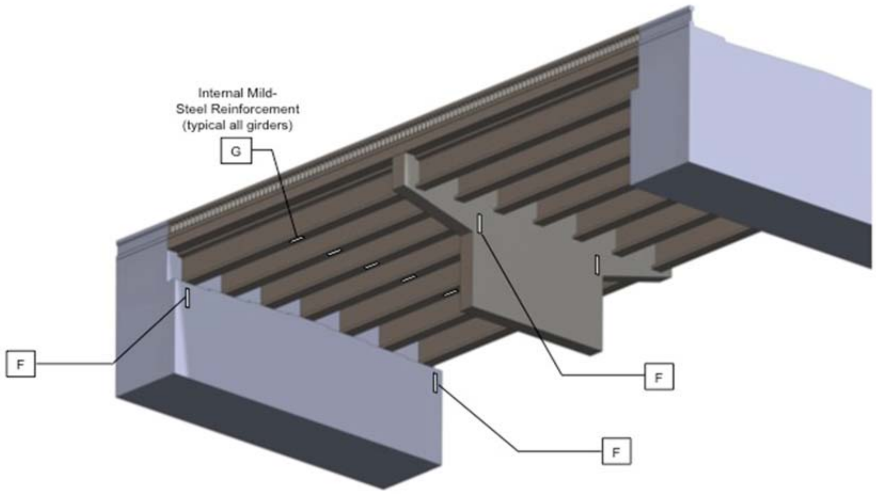


Figure 7.23: Precast concrete bridge instrument layout bottom isometric

One can think of the sensor layout and types shown in Figures 7.22 and 7.23 as potential instrumentation scenarios for a typical precast girder, cast-in-place bridge superstructure with interior pier and bench-type abutments. If three of these structures were to be instrumented within a smart infrastructure corridor, this instrumentation scenario can be replicated at each location. It should be emphasized, however, that all bridges of this configuration within the corridor might not need to be instrumented. It may be appropriate to instrument one bridge of this type and extrapolate information garnered from monitoring this bridge to others within the corridor.

Table 7.2 indicates there are many types of sensors present in the bridge superstructure and substructure. Some sensors are redundant and others provide the distinction between data to be collected on dynamic horizons (i.e., short acquisition cycles) and others have longer horizons (i.e., very long acquisition rates)—this is the motivation for two types of strain sensors in the bridge deck. Resistive-type strain sensors can capture dynamic behavior through high sampling rates, and vibrating wire strain gages are intended to gather data with sampling rates that are much longer.

It should be noted that the instrumentation array must be validated periodically to ensure proper function of the instruments; therefore, periodic load testing (French et al. 2010) must be incorporated into the program to validate the instrumentation functionality and to provide calibrated comparison with baseline testing data. Such load tests are common (Foley et al. 2010).

Table 7.2: Sensor Descriptions and Construction Timing.

Sensor	**Measurement and Objective**	**Sensor Type, Location, and Potential Provider**	**Construction Timing**
A	Strain – dynamic Dynamic distribution of wheel loads within bridge deck and transverse strain during curing process and long-term strains. Assessment of superstructure continuity and load distribution within superstructure.	Spot-Weldable Resistive Strain Gage Mounted to internal deck reinforcing steel at locations of positive bending (between girders) and negative bending (over girders). Also, mounted to continuity reinforcement within bridge superstructure. Vishay Precision Group (http://www.vishaypg.com) 	Sensor needs to be installed on bridge deck internal reinforcement and on bridge deck continuity steel at time of placement within bridge deck. Spot-welding of each sensor onto ground areas of reinforcing steel needs to be done prior to concrete placement. Concrete placement procedure needs to accommodate strain gage wiring exits.
B	Strain – long term Distribution of transverse strains in bridge deck resulting from creep, shrinkage, and temperature variation within bridge deck. Assessment of long-term strains resulting from creep, shrinkage and temperature.	Spot-Weldable Vibrating Wire Strain Gage Mounted to internal deck reinforcing steel at locations of positive bending (between girders) and negative bending (over girders). Also, mounted to continuity reinforcement within bridge superstructure. Durham Geo Slope Indicator (http://www.slopeindicator.com) 	Sensor needs to be installed on bridge deck internal reinforcement at time of placement within bridge deck.

Table 7.2: Sensor descriptions and construction timing (continued).

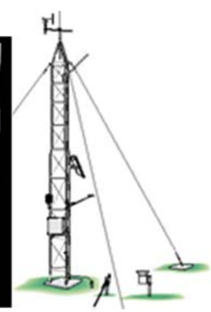
Sensor	**Measurement and Objective**	**Sensor Type, Location, and Potential Provider**	**Construction Timing**
C	Road Surface Conditions Measure road surface temperature, water films levels, and road surface conditions (dry/damp/wet/ice).	Luffts IRS21 Road Surface Sensor Mounted at two locations in bridge deck near the surface. Campbell Scientific (http://www.campbellsci.com) 	Road surface puck needs to be installed at the time the bridge deck is placed and just before final finishing. Wiring runs from sensor need to be accommodated.
D	Environmental Conditions Measure wind speed, wind direction, relative humidity, and temperature.	Vaisala WXT520 Weather Transmitter and Instrument Tower Mounted in proximity to smart structure corridor component. Campbell Scientific (http://www.campbellsci.com)  	Can be installed any time during the corridor sequence of construction. ASOS site information can be used in lieu of weather station if deemed appropriate.
E	Sensor label not used.		

Table 7.2: Sensor descriptions and construction timing (continued).

Sensor	Measurement and Objective	Sensor Type, Location, and Potential Provider	Construction Timing
F	Substructure Inclination Measure tilt of substructure components (e.g., tilt of bench-type abutment, rotation of interior pier).	Electrolytic Tilt Sensor Mounted to Durham Geo Slope Indicator (http://www.slopeindicator.com)  Horizontal Beam Sensor  Vertical Beam Sensor  Tiltmeter	Sensor can be placed post construction of abutment, interior pier and superstructure. Accommodations need to be made for wiring runs (e.g., exterior conduits).
G	Strain – dynamic Longitudinal strain in precast concrete girders. Strain measurements can be used to assess load distribution among girders in the superstructure and longitudinal temperature induced strains, creep strains, prestress loss, and shrinkage induced strains in the girders.	Spot-Weldable Resistive Strain Gage Mounted to internal mild reinforcing steel at 0.4L locations of precast concretet bridge girders. Mounting to be done on lowest mild-steel longitudinal reinforcing bars present in the prestress concrete girder. Vishay Precision Group (http://www.vishaypg.com) 	Sensors must be installed at the time the precast girder is cast. Accommodations for wiring exiting the girder need to be made. Post-girder erection will require conduit runs for wires.

It should be emphasized that two types of strain gages within the instrument array should be provided. Aside from the need to measure both long-term and dynamic strains in the bridge deck, these two sensor types can be used during the period load testing to calibrate one another.

7.3.4 Data Flow and Storage

There will be a significant level of data acquired for this typical infrastructure component. The sensors described earlier must have their information logged using a data logger. The data logger will sequence and timestamp the data for subsequent storage. Figure 7.24 illustrates the typical data acquisition hardware and data flow for this smart corridor component.

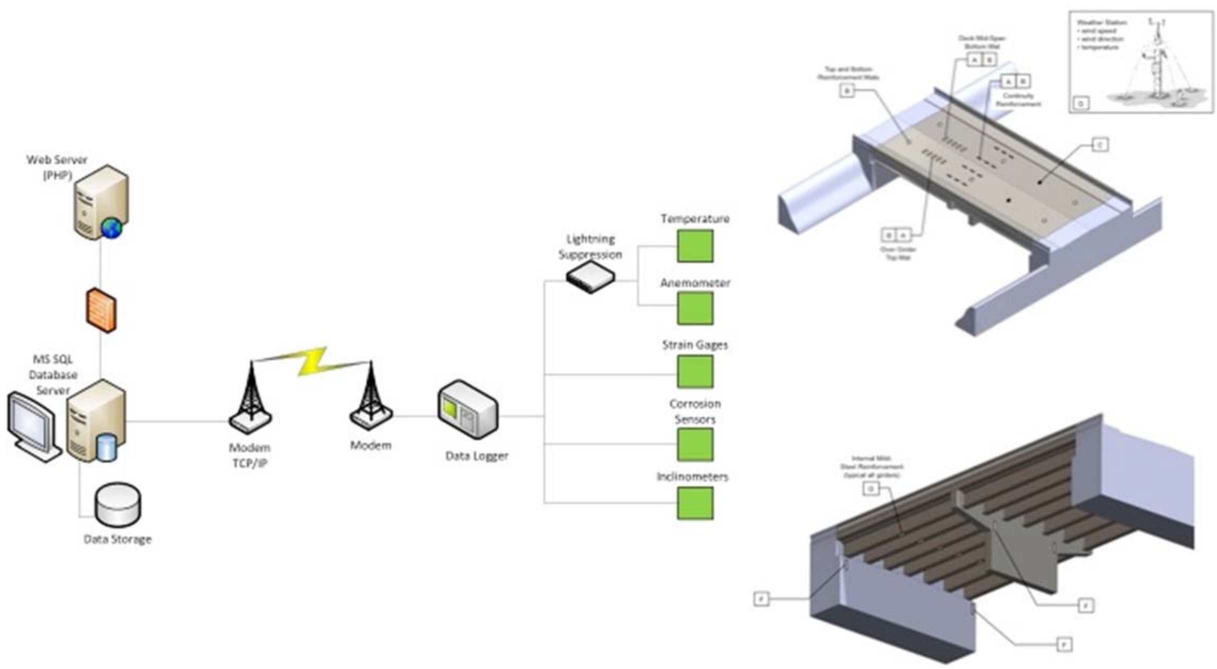


Figure 7.24: Precast concrete bridge component data flow

It should be noted that accelerometers are present in the figure, but are not necessary for this type of superstructure component.

The sensors shown in this smart corridor component will likely need to be hardwired to the logger, which may or may not have power available at the site; it is assumed that power will be available. It should be noted that solar panels or marine-type batteries can be used as power sources in remote locations; the number of sensors to be used, however, will dictate the type and number of solar panels and batteries required to deliver power to the sensor array.

The data logger can be programmed to acquire data with threshold triggers. Alternatively, data can be acquired continuously with averaging or another data decimation technique being applied to limit data flow through the logger to storage.

Wireless transmission of data from the logger location to the remote storage or display location is most effectively conducted using modem connectivity via cell phone, as cell phone modem transmission improves the length over which the data can be wirelessly transmitted. A hardwired connection from logger to storage (e.g., fiber optic backbone) could also be used.

Once the data lands at the storage location, it is likely that a SQL or other database system will be designed to generate long-term storage of the data for historical record. It is also likely that data can be sent to Web-based interfaces for real-time display.

7.4 Geotechnical Structures

The following geotechnical structures are identified as important to WisDOT:

1. Retaining walls: Mechanically Stabilized Earth (MSE) walls and post and panel walls
2. Bridge abutments
3. Bridge piers
4. Piles
5. Embankments
6. Slopes
7. Shallow foundations (footings)
8. Foundations for sign structures

Geotechnical parameters that are significant to design, construction, and maintenance of geotechnical structures include: strains in members such as piles; reinforcing elements in MSE walls; vibrations in piers and piles; corrosion of piers and piles; scour of soil around piers and piles; soil and water pressures in backfill and foundation soils; settlement under walls and in backfill materials; and lateral and vertical movement of walls. Table 7.3 summarizes the geotechnical data elements important for MSE walls and reinforced slopes.

A Mechanically Stabilized Earth (MSE) wall is a reinforced soil, in which soil is placed and compacted in layers as layers of reinforcing elements (steel strips, geotextile sheets, steel or polymeric grids) are placed within the soil. Figure 7.25 shows the major elements of MSE walls, which are mechanically stabilized earth, reinforcing elements, modular block facing, and retained backfill. MSE walls are commonly used in Wisconsin.

MSE technology is also applied for constructing berms and steep slopes. MSE walls have lower construction costs; however, Koerner and Koerner (2011) reported that 2 to 4% of MSE walls exhibited excessive deformation or collapse. MSE wall failures are mainly due to internal or external instabilities of the reinforced soil zone. Implementation of health monitoring plans for MSE walls will help in understanding how failure progresses and in better understanding the wall behavior.

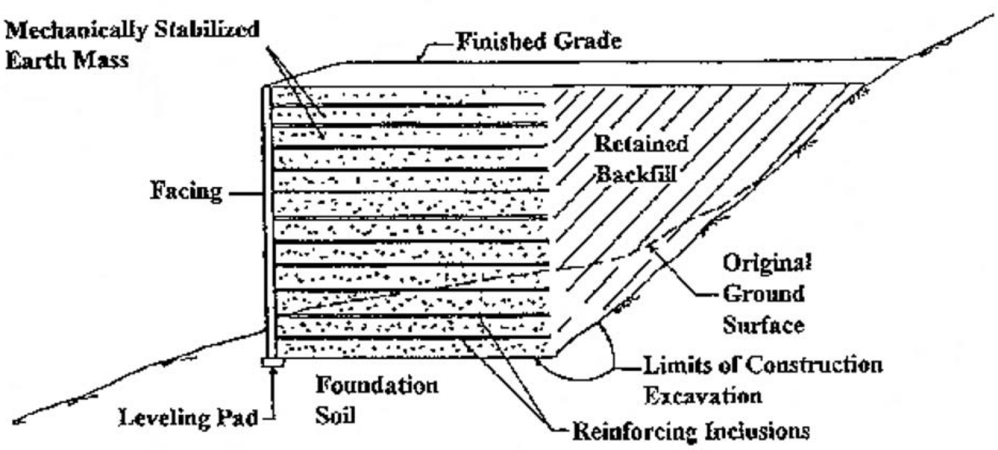


Figure 7.25: Generic cross-section of a MSE structure with principal elements (Elias et al., 2001)

7.4.1 Types of Monitoring

Koerner and Koerner (2011) discussed instrumentation for MSE walls, berms, and slopes and presented the following:

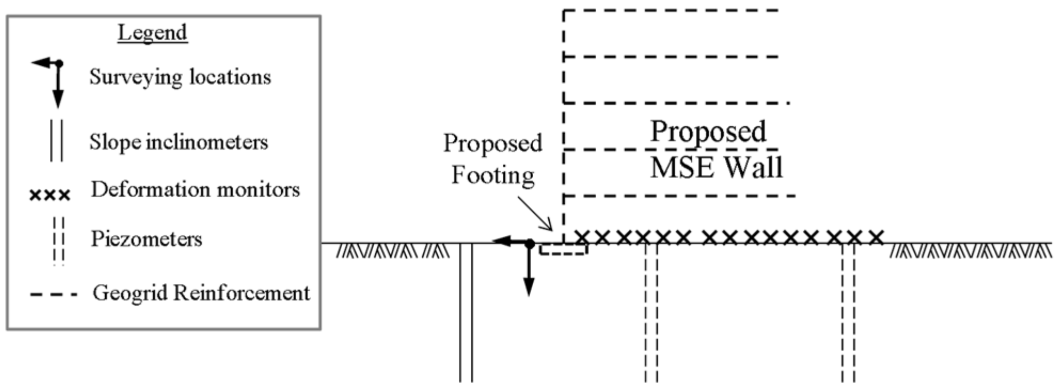
1. Basic surveying: monitor both vertical and lateral movements
2. Continuous deformation monitoring of deformation in the reinforcement
    a. strain gages and fiber optic technology
    b. electrical strain gages are applied to geo-grids and geotextiles by adhesive bonding or mechanical attachment
    c. for optic measurements, glass fibers or poly-optical fiber are applied to geo-synthetic by weaving or knitting
3. Slope Indicators: used to monitor lateral deformations
4. Piezometers: measure change in pore water pressure in a saturated soil mass

Koerner and Koerner (2011) stated that the vibrating wire piezometers are reliable and can be placed before construction under the highest portion of the wall, berm, or slope. Piezometers can also be placed in the foundation soil in front of the toe of the structure. Normal measurements will indicate a decrease in pore water pressure, and, therefore, an increase in effective stresses. Increasing pore water pressure indicates poor drainage and should be a cause for concern.

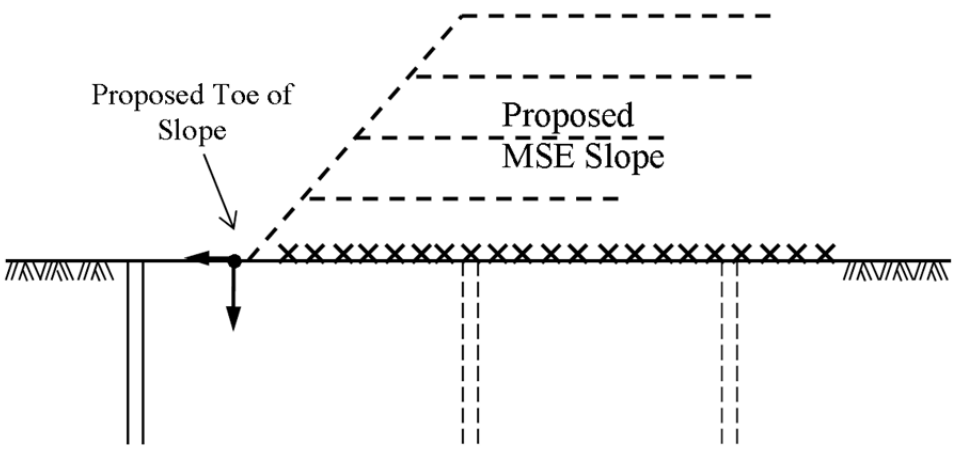
7.4.2 Instrumentation for MSE Walls and Slopes

Among the important issues for implementing a monitoring plan for MSE walls and slopes are the timing of installation and locations of sensors. For timing, instrumentation before construction, and instrumentation during and after construction should be considered.

Figure 7.26 depicts the instrumentation plan for MSE walls, berms, and MSE slopes before construction. Monitoring foundation soil deformation and pore water pressures are important to establish benchmark values before construction to characterize the long-term behavior of MSE walls.



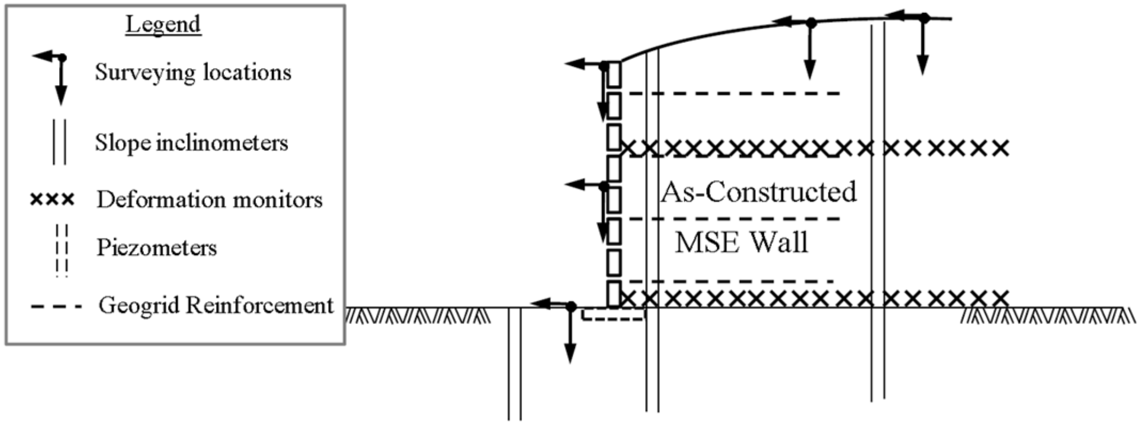
(a) Recommended layout for MSE walls and berms



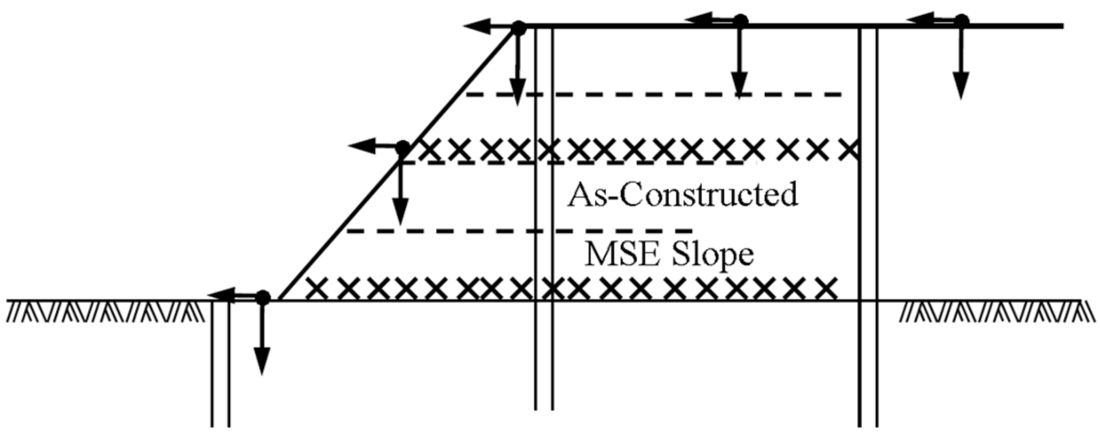
(b) Recommended layout for MSE slopes

Figure 7.26: Recommended layout of instrumentation to monitor potential movements before construction (Koerner and Koerner, 2011)

During walls construction, installing surveying monuments are important to monitor the wall's movement. Instrumentation to monitor wall movement, deformation, and water pressure are shown in Figure 7.27. Elias et al. (2001) presented a summary of possible instruments for monitoring reinforced soil structures (Table 7.3).



(a) Recommended layout for MSE walls and berms



(b) Recommended layout for MSE slopes

Figure 7.27: Recommended layout of instrumentation to monitor potential movements during and after construction (Koerner and Koerner, 2011)

Table 7.3: Possible instruments for monitoring reinforced soil structures (Elias et al. 2001)

PARAMETERS	POSSIBLE INSTRUMENTS
Horizontal movements of face	Visual observation Surveying methods Horizontal control stations Tiltmeters
Vertical movements of overall structure	Visual observation Surveying methods Benchmarks Tiltmeters
Local movements or deterioration of facing elements	Visual observation Crack gauges
Drainage behavior of backfill	Visual observation at outflow points Open standpipe piezometers
Horizontal movements within overall structure	Surveying methods (e.g. transit) Horizontal control stations Probe extensometers Fixed embankment extensometers Inclinometers Tiltmeters
Vertical movements within overall structure	Surveying methods Benchmarks Probe extensometers Horizontal inclinometers Liquid level gauges
Performance of structure supported by reinforced soil	Numerous possible instruments (depends on details of structure)
Lateral earth pressure at the back of facing elements	Earth pressure cells Strain gauges at connections Load cells at connections
Stress distribution at base of structure	Earth pressure cells

Table 7.3 (Cont.): Possible instruments for monitoring reinforced soil structures (Elias et al. 2001)

PARAMETERS	POSSIBLE INSTRUMENTS
Stress in reinforcement	Resistance strain gauges Induction coil gauges Hydraulic strain gauges Vibrating wire strain gauges Multiple telltales
Stress distribution in reinforcement due to surcharge loads	Same instruments as for stress in reinforcement
Relationship between settlement and stress-strain distribution	Same instruments as for: • vertical movements of surface of overall structure • vertical movements within mass of overall structure • stress in reinforcement Earth pressure cells
Stress relaxation in reinforcement	Same instruments as for stress in reinforcement
Total stress within backfill and at back of reinforced wall section	Earth pressure cells
Pore pressure response below structures	Open standpipe piezometers Pneumatic piezometers Vibrating wire piezometers
Temperature	Ambient temperature record Thermocouples Thermistors Resistance temperature devices Frost gauges
Rainfall	Rainfall gauge
Barometric pressure	Barometric pressure gauge

7.4.3 Health Monitoring Plans for Geotechnical Structures

This section discusses structural health monitoring plans for geotechnical infrastructure. Data elements important to geotechnical design, construction and maintenance were identified and the corresponding instrumentation plans are provided. Geotechnical infrastructures include retaining walls, bridge abutments, piers, piles, slopes, and embankments.

7.4.3.1 Retaining Walls

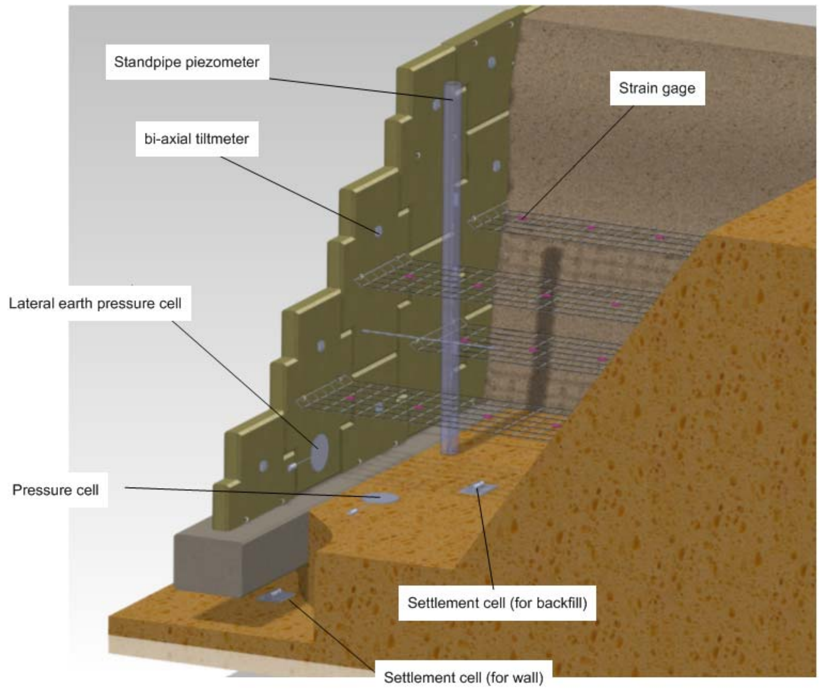
Health monitoring plans have been developed for MSE walls and post and panel retaining walls. Plans proposed for MSE walls can also be used for reinforced slopes and berms.

Instrumentation can be applied for MSE walls with critical design such as high walls, walls with large surcharge loads, and walls on soft foundations. Monitoring before construction will provide benchmark values for long-term monitoring of the behavior of MSE walls and slopes. Figure 7.28 shows a proposed plan of instrumentation for monitoring the health of an MSE wall. Before constructing MSE walls, surveying monuments for elevation and lateral position are placed with recommended location 3 to 6 ft. from the toe of the wall and should be repeated every 50 to 100 ft. Slope inclinometers and piezometers are recommended to be installed in front of the highest section of the wall and underneath the fill at that location.

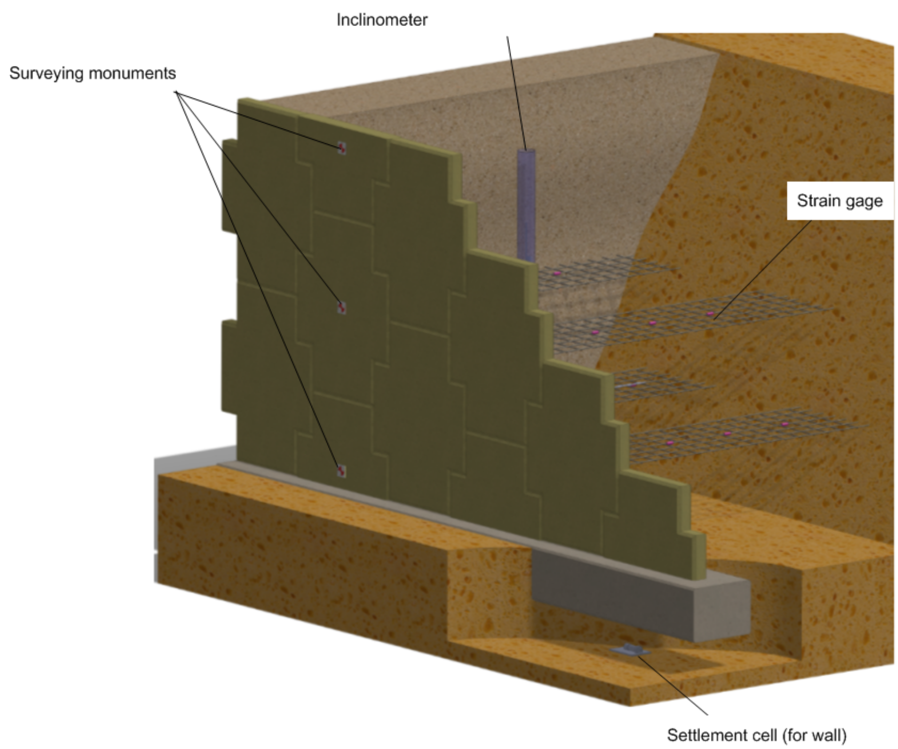
Surveying monuments are installed on the modular panels of the wall, as depicted in Figure 7.28(b), to monitor horizontal movement of the facing and vertical movement of the overall structure. Tilt-meters are installed on each modular panel along the highest sections of the walls, which will provide information about the horizontal movement of the facing and the vertical and horizontal movements of the entire structure. In addition, inclinometers can be installed in the reinforced backfill to monitor the horizontal movement of the wall.

Earth pressure cell can be installed in the orientations depicted in Figure 7.28(a) to monitor lateral earth pressure on the facing of the walls at the highest location and the vertical stress at the bottom of the wall due to backfill and surcharge loads. Strain gages are installed on the reinforcing elements to monitor strain and calculate stresses within these elements. Settlement cells can be installed underneath the wall and under the reinforced backfill to monitor settlement of the wall and backfill. Piezometers are important to monitor pore pressures within the fill and in the foundation soil. Poor drainage conditions and pore pressure buildups can lead to wall failure.

Data flow and storage plans for an instrumented MSE wall are shown in Figure 7.29, and are similar to the discussion presented in Section 7.3.4 Data Flow and Storage.



(a) Instrumentation for reinforced soil, facing and reinforcing elements



(b) Front view with surveying monuments

Figure 7.28: Instrumentation plan for MSE walls

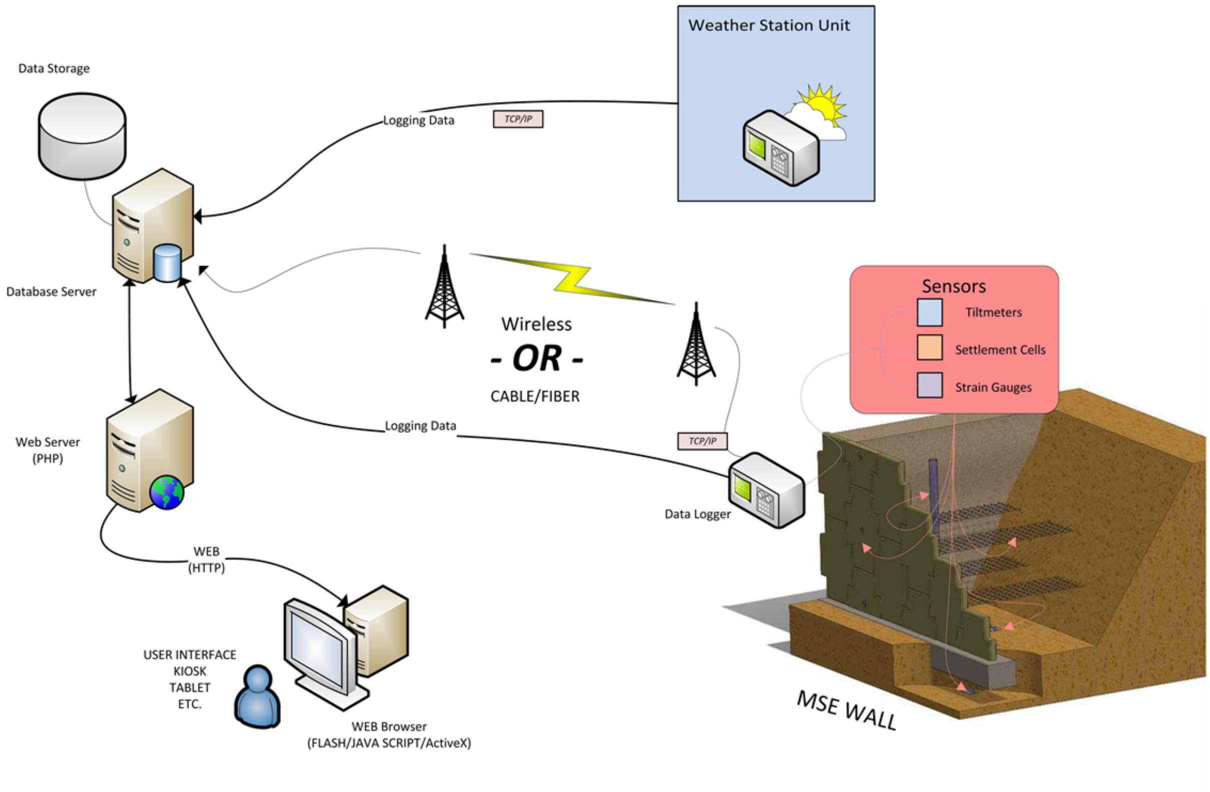


Figure 7.29: Diagram of data flow and storage for instrumented MSE wall

Health monitoring instrumentation plans are also developed for post and panel retaining walls, as shown in Figure 7.30. Sensors include biaxial tiltmeters installed on steel H-piles to monitor horizontal and vertical movement of the wall. Settlement sensors are installed under the retained soil to monitor vertical movement. Load cells and piezometers are also installed to measure soil and water pressures behind the walls. For retaining wall health monitoring, weather stations are also installed, as shown in Figure 7.29.

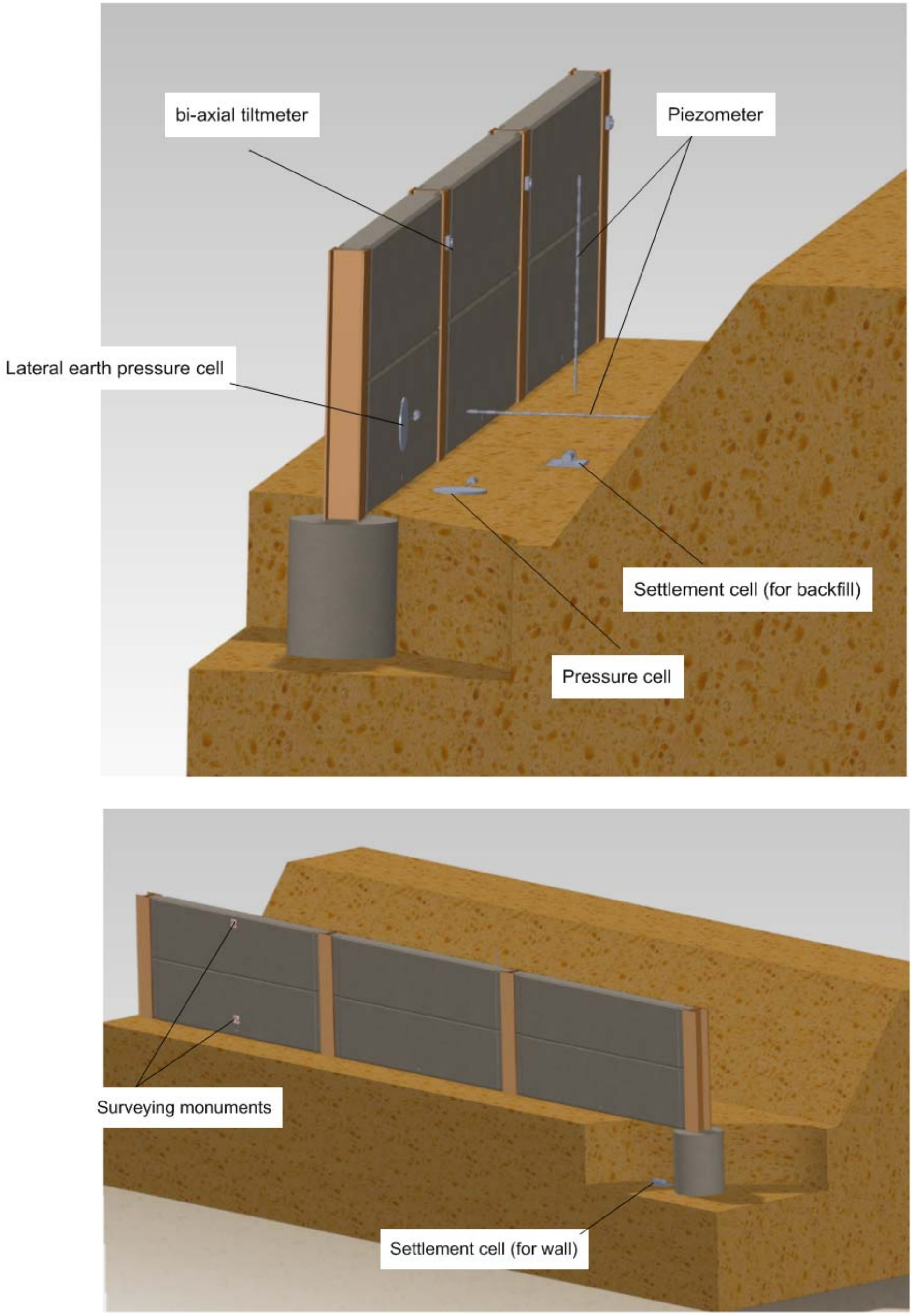


Figure 7.30: Instrumentation plan for post and panel retaining walls

7.4.3.2 Piers and Piles

WisDOT uses multi-columned piers to support bridge structures. These columns are supported by steel H-piles or pipe piles in a pile group with pile cap. Data elements important to design, construction, and maintenance of bridge substructures include vertical and horizontal movements/tilt of pile cap and piles, vibrations of the pier, corrosion of the pier and pile cap, scour of the soil around the pier, strain and stresses in piles. Figure 7.31 shows an instrumentation plan developed for monitoring the structural health multi-columned piers over steel H-piles and pipe piles.

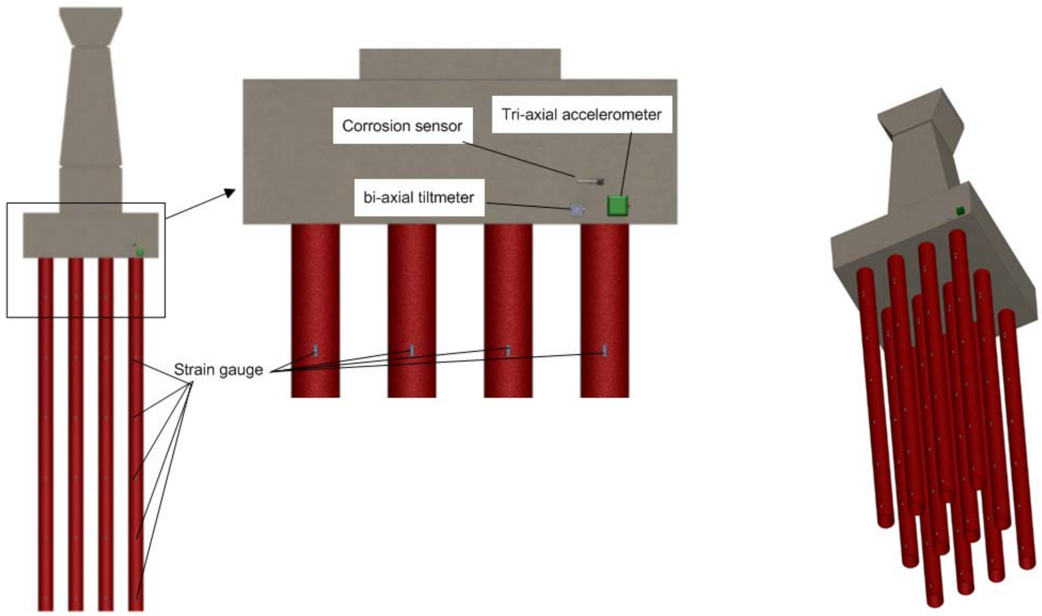


Figure 7.31: Instrumentation plan for multi-columned pier

Figure 7.32 shows the instrumentation plan for monitoring the health of a pile bent with steel H-piles; such pile bent is commonly used as bridge abutment behind MSE walls. Sensors installed include strain gages to monitor strain and stress in steel piles, tilt-meters to monitor vertical and lateral movements of the pile bent, corrosion sensors, and tri-axial accelerometers to measure vibrations.

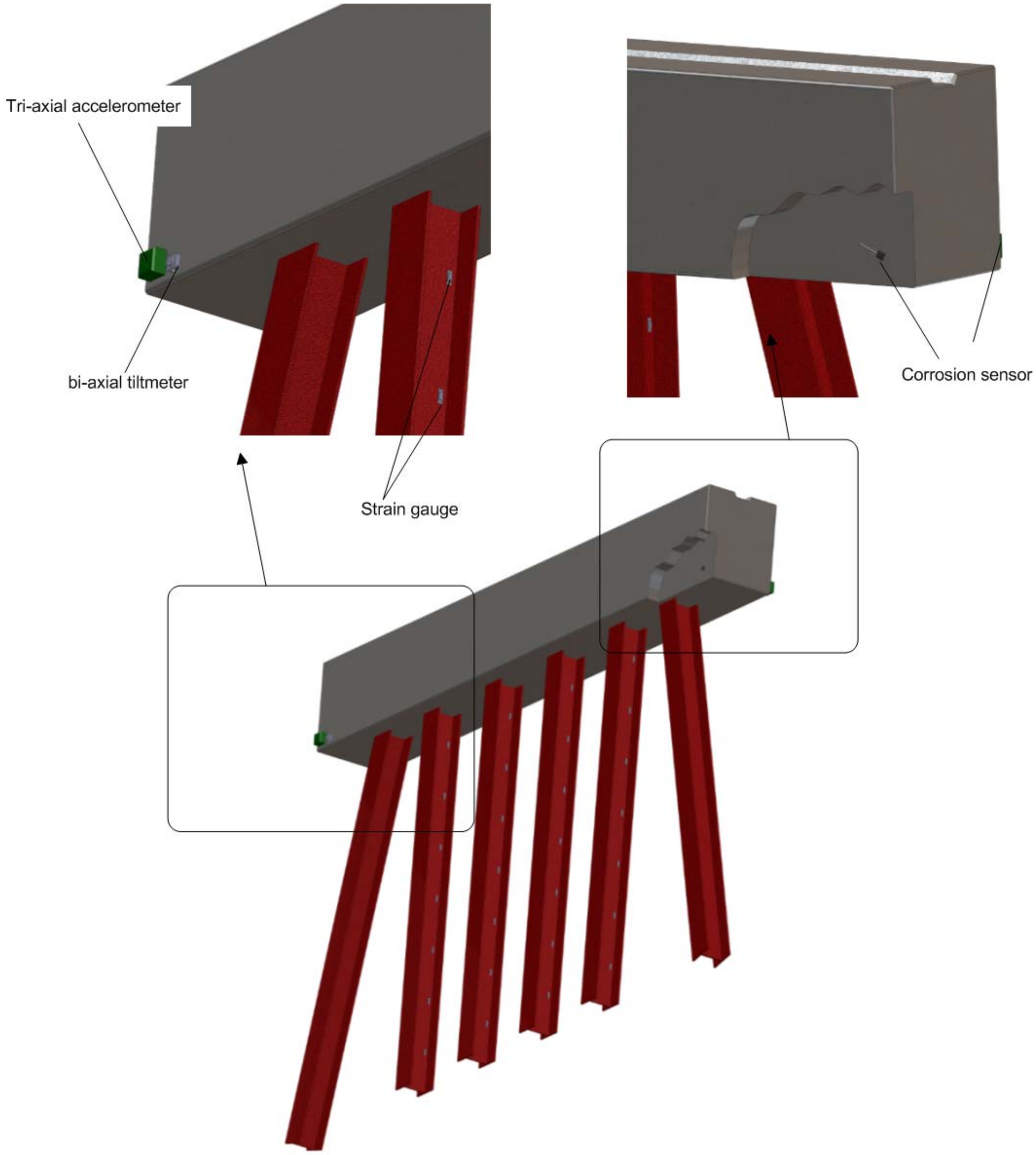


Figure 7.32: Instrumentation plan for pile bent

7.5 Cost Estimates for Infrastructure Health Monitoring Plans

The infrastructure health monitoring plans developed earlier in this report for pavements, bridge structures, and geotechnical structures are the major component of the testbed. These plans were analyzed to provide reasonable cost estimates based on the current market conditions. It should be noted that the sensor technology is advancing in an accelerated rate and prices are continuously changing, but with a reasonable margin.

7.5.1 Pavement Structures

Table 7.4 provides a detailed cost estimate for the instrumentation of four travel lanes (two in each direction) at one location within the Zoo Interchange. The instrumentation provided in this estimate, minus the weather station, can be replicated to include all four legs of the interchange.

7.5.2 Bridge Structures

The instrumentation plans for bridge structures were provided in Figures 7.22 to 7.24, and a detailed description of the selected sensors was presented in Table 7.2; all of these plans are for bridge superstructure. Table 7.5 presents a cost summary for sensors used in the plans of Figures 7.22-7.24 and referenced in Table 7.2. In addition, Table 7.6 presents cost estimates for alternative selections of sensors.

Selecting sensors may require input from companies/contractors who are experienced with installation of IHM systems. Companies/contractors with specific experience could provide useful information with regard to sensor durability, cost, maintenance, and any other relevant information. As an example, the research team identified two companies with such experience:

1. Applied Geomechanics, Inc. (http://www.carboceramics.com/appliedgeomechanics/)
2. Bridge Diagnostics, Inc. (http://www.bridgetest.com/)

For example, pertaining to the information presented in Table 7.5, personal communication with Bridge Diagnostics, Inc. indicated that weldable strain gages are very difficult to install under field conditions. In addition, Geokon, Inc. (sensor manufacturer) introduced a combined piezo-resistive/VW sensors that further reduces the installation time (cost). This combined gage is not advertised by Geokon, but it does exist. For the bottom flange moment gages (Reference G in Table 7.6), a BDI strain transducer can be used, as it is faster to install (reducing labor expenses).

Table 7.4: Estimated Pavement Instrumentation Costs

ITEM	Unit Cost	Total Cost
WIM Sensors		
4 Traffic loops w / amplifiers	$350	$1,400
4 Quartz piezo-electric strips w / amplifiers	$7,375	$29,500
8 Piezo-electric strips w / amplifiers	$725	$5,800
1 Camera	$2,525	$2,525
		$39,225
Weather Station		
Weather Hawk integrated weather station	$2,059	$2,059
		$2,059
Power Supply		
Solar charged power supply	$2,500	$2,500
		$2,500
Communications		
Radio modem	$300	$300
60-month cellular data plan	$75	$4,500
		$4,800
Pavement Sensors		
4 Temperature / relative humidity sensor trees	$475	$1,900
8 LVDT-based deflection sensors w/amplifiers	$1,200	$9,600
24 Vibrating Wire strain sensors	$125	$3,000
24 Dynamic resistive strain sensors	$400	$9,600
16 Interface pressure sensors	$350	$5,600
		$29,700
Subgrade Sensors		
4 Subgrade moisture sensors	$165	$660
4 Subgrade temperature sensors	$100	$400
		$1,060
Data Acquisition System		
CR 9000 logger w/ Software & 7 year warranty	$11,875	$11,875
5 9050 data cards w / 7 year warranty	$1,481	$5,925
3 9060 Excitation modules w / 7 year warranty	$1,750	$5,250
AVW200 Vibrating Wire Spectrum Analyzer Module	$460	$460
1 SDMSIO1 CSL 1-channel serial I/O module	$330	$330
2 AM1632b relay multiplexer w / 7 year warranty	$708	$1,415
24 Completion resistor modules	$65	$1,560
		$26,815
TOTAL ESTIMATED COST		**$106,159**

Table 7.5: Cost estimate for sensors used in plans for bridge superstructure as referenced in Table 7.2

Reference to Table 7.2	Gage Type	Unit Price	Quantity	Extended Price	Notes
A	Strain- 1/4 Arm (includes completion unit)	$560	22	$12,320	
B	Strain- VW	$150	22	$3,300	
C	Road Condition	NA			
D	Weather	$1,400	1	$1,400	Sensors
		$2,800	1	$2,800	Tower (approximate- will change with location, height, tiedowns, etc.)
F	Tilt	$1,400	6	$8,400	
G	Strain- 1/4 Arm	$560	7	$3,920	
	Cable	$0.82	5000	$4,100	Assumes 150' per sensor
			Total	**$36,240**	

Table 7.6: Cost estimate for alternative sets of sensors used in plans for bridge superstructure, as referenced in Table 7.2

Reference to Table 7.2	Gage Type	Unit Price	Quantity	Extended Price	Notes	Advantage
A	Strain- 1/4 Arm (includes completion unit)	$900	22	$19,800	Combined Geokon Foil/VW 'Sisterbar'	No field welding & more durable (reduces installation time dramatically)
B	Strain- VW					
C	Road Condition	NA				
D	Weather	$1,400	1	$1,400		
		$2,800	1	$2,800		
F	Tilt	$1,400	6	$8,400		
G	Strain- 1/4 Arm	$470	7	$3,290	BDI ST350 Strain Transducer	More stable, much less field install time
	Cable	$0.82	5000	$4,100	Sensor Cable	
			Total	**$39,790**		

7.5.3 Geotechnical Structures

Cost estimates for instrumenting the MSE wall, presented in Figures 7.28 and 7.29, are shown in Table 7.7. In order to obtain an axial load in the geo-fabric, two strain gages must be installed at the same location and averaged. In this particular case, the strain gage Geokon 4000 series was selected; however, there are other alternatives based on the actual type of geo-fabric used.

Installing piezometers requires drilling boreholes, which is expensive; in this case, a WisDOT drill rig could be used. In terms of time requirements, typically 1-2 piezometers can be installed per day, depending on the depth of sensors. Among the sensors presented in Table 7.7, the settlement systems are relatively expensive. A cost/benefit analysis may need to be considered when selecting these systems for implementation.

Table 7.7: Cost estimates for MSE wall instrumentation plan

Gauge Type	Unit Price	Quantity	Extended Price	Notes
Strain Gauge	$185	32	$5,920	Geokon 4000 series Need two gages to obtain axial strain Assume 4 elevations, 4 cross-section, 2 per location
Piezometer	$700	3	$2,100	Geokon 4500S
Earth Pressure Cell	$725	6	$4,350	Geokon 4810 Back plate for mounting on rigid surface
	$800	3	$2,400	Geokon 4800 Flexible on both side for mounting within fill
Tiltmeter	$1,400	12	$16,800	Assume 3 elevations, 4 cross-sections
Settlement System	$6,200	1	$6,200	Geokon 4650 This will vary a lot with mounting location of reference cylinder (price assumes 3 measurement locations)
Cable	$0.84	10000	$8,400	Assume 175' per gauge
		Total	**$46,170**	

Cost estimates for substructure plans presented earlier (bridge pier, pile foundation, pile cap, etc.) are presented in Table 7.8

Table 7.8: Cost estimates for substructure instrumentation plan

Gage Type	Unit Price	Quantity	Extended Price	Notes
Strain Gages (VW)	$185	32	$5,920	Geokon 4000 series strain gage-dead load is primary load. Dynamic measurements will not tell much. Assume 4 piles, with 4 cross-sections of 2 gages (axial measurements only)
Tri-axial accelerometer	$980	2	$1,960	Accelerometer
Tilt-meter	$1,400	1	$1,400	
Corrosion Sensor	TBD			
Cable	$0.84	5200	$4,368	Assumes 150' per sensor
		Total	**$13,648**	

7.5.4 Data Acquisition

Table 7.9 presents cost estimates for a data acquisition system that can be used to support the instrumentation plans of bridge and geotechnical structures described earlier. The following should be noted for this data acquisition system:

1. Two types of signal conditioning are required: piezo-resistive and vibrating wire. Piezo-resistive sensors must be run back to the datalogger and the vibrating wire gages can be ‘multiplexed’. Multiplexing allows the same signal conditioning to be used for every sensor and also reduces the length of cable needed.

2. The cell modem is used to transfer the data from the site to the remote storage location. This is the most cost-effective method for data transfer and allows nearly any location to be connected with remote storage location.

3. The traffic cabinet ensures the equipment is secure and cannot be stolen or vandalized.

4. Power conditioning is the ‘backup’. The system can be run on solar power, however, AC is preferred if it can be obtained economically. If AC power will be a significant investment, then solar power can always be used. In any case, a significant amount of power conditioning and backup is installed to ensure the system has power during outages.

Table 7.9: Cost estimates for data acquisition system

Piezo-resistive Data Acquisition	$18,000	1	$18,000
VW Multiplexers	$1,400	7	$9,800
VW Signal conditioning	$500	1	$500
Cell Modem	$1,200	1	$1,200
Traffic Cabinet	$1,100	1	$1,100
Power Conditioning	$1,000	1	$1,000
		Total	**$31,600**

7.6.5 Cost of Web Based Data Viewing

The IHM website can be launched by the owner of the structure being monitored, or existing Web sites developed by consultants can be used. Table 7.10 presents such cost estimates, including software.

7.5.6 Cost of Labor/Installation

Cost of labor can be divided into the following:

1. Fees to develop instrumentation plan/design, constructions drawings, etc. Typical fees range from $5,000 to $10,000.
2. Installation cost depends on the number of visits by the installation contractor during construction. Several trips to the site may be required depending on the projects type. Table 7.11 presents installation cost estimates for a typical sensors presented in the instrumentation plans discussed earlier
3. Maintenance costs account for incidents that may affect the system such as electrical storms, vandalism, etc. Maintenance can be performed in-house when the owner has significant number of systems. Consultant costs per maintenance trip range between $2,500 and $5,000.
4. Data interpolation cost. Depending on the use of the system, data interpolation may require an engineer to look at data every day or once per month.

Table 7.10: Cost of Web-based data viewing

Consultant Hosts Data (includes cell modem fees)	$125-250 per month
Cell Fees (typical if client provides service)	$50 per month
Hosting Software (if client wants to host data site)	$10,000 - $30,000

Table 7.11: Installation fees using specified sensors in earlier presented plans

Task	**Duration**	**Mobilization**	**Fee Range**
Bridge Specified Inst.			
Deck Casting	1 week	3	$13,000
Beam Casting	2 days	4	$6,000
Final Install	1 week	5	$18,000
MSE Instrumentation	1 week	2	$13,000
Piezometer install (drill rig)	2 days	1	$3,500
Pile Instrumentation			
Sub Terrain Pile Sensors	4 Days	1	$8,500
Bent Cap (done during 'final install')	-	5	-
		Total	**$62,000**

Chapter 8

Marquette Interchange Data Analysis

8.1 Background

The analysis of a load related response (i.e., stress and strain) from any instrumented infrastructure component (e.g., highway or bridge section) requires an understanding of the location, magnitude and speed of the applied loading. Information on the load magnitude and speed is commonly obtained via a Weigh-In-Motion (WIM) system imbedded in the pavement surface. Load placement information may be obtained using imbedded sensor strips similar to those used for WIM systems.

The Wisconsin Highway Research Program (WHRP) recently completed Study 0092-06-01 (2008) which examined the perpetual pavement system constructed within the north leg of the Marquette interchange (WHRP project 0092-06-01). As part of this study, wheel wander and WIM systems were imbedded in the pavement surface to document the applied wheel loadings. Figure 8.1 provides a schematic illustration of these two systems. Figure 8.2 provides a recent snapshot of these two systems after approximately 5-1/2 years of trafficking. Information from the wander/WIM systems was used in conjunction with pavement stress and strain measurements to provide a mechanistic assessment of the expected fatigue performance of this HMA pavement. Pavement loading/response data was collected for a period of approximately two years and stored in an accessible database. The field study was decommissioned in 2009 and the primary data collection components were removed from the roadside cabinet. The imbedded wander and WIM sensors were left within the pavement surface with lead wires extending to the roadside cabinet.

A sample data stored within the WHRP project 0092-06-01 database was extracted for this study to address two basic informational needs:

1. How are vehicle loads distributed within the pavement lane and how do these placements vary by vehicle type and time of day?
2. What are the spectra of applied loadings that can be used as inputs for a mechanistic analysis of pavement performance?

In addition to the above, the data collection components were re-engineered and re-deployed to allow for the collection of real-time response data from the imbedded wander and WIM systems to help answer the following: Can the lower-cost piezo strips be used as a surrogate for the quartz piezo strips to collect accurate wheel load data?

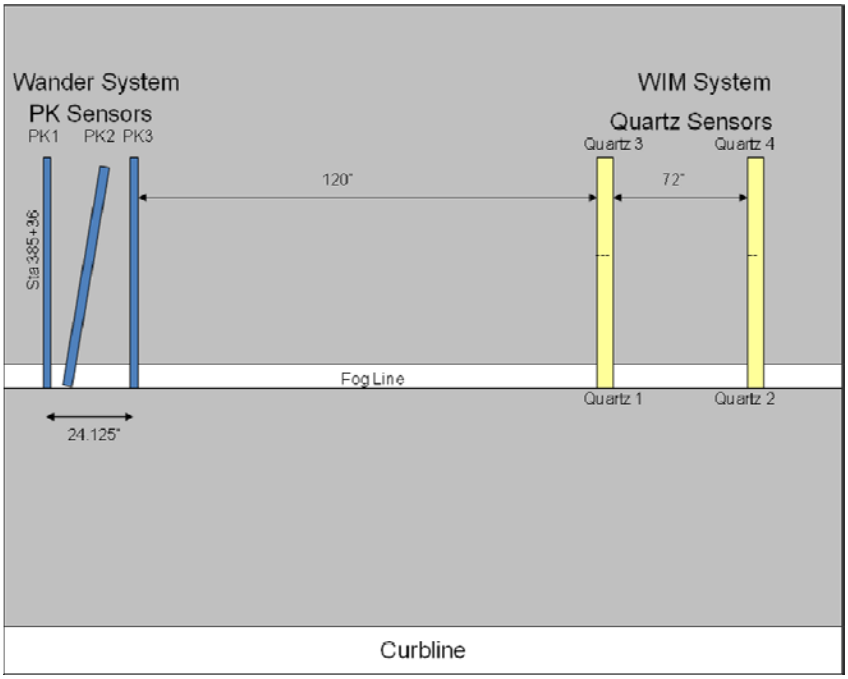


Figure 8.1: Schematic Illustration of the Wander and WIM Systems Imbedded Within the North-Leg of the Marquette Interchange

Figure 8.2: Wander and WIM Systems After 5-1/2 years of Trafficking

8.2 Wheel Wander Analysis

As vehicles travel along a pavement section there is a natural tendency for them to shift within the lane of travel. The variation in placement location, termed wheel wander, is commonly assumed to be normally distributed and described by a mean location and standard deviation of placement. In general, as the load placement moves to the outer edge of the lane, the induced stresses, strains and deflections increase significantly, particularly in jointed concrete pavements (JCP). To counteract this effect, JCP pavements in Wisconsin are typically constructed with a 14-ft wide outer lane, with the fog line striped at 12-ft and the outer 2-ft incorporating built-in rumble strips. This, in effect, keeps the edge loadings at least 2-ft away from the outer edge, significantly reducing applied stress, strains and deflections.

The Mechanistic-Empirical Pavement Design Guide (MEPDG) software incorporates default values for the mean placement location, as measured from the painted fog line, and the standard deviation, which are 18-in and 10-in, respectively. The MEPDG software utilizes single inputs for these values, hence there are no adjustments for vehicle type, time of day, travel speed, etc. To assess the validity of these default values, the WHRP 0092-06-01 database was queried to extract a representative sample of wheel placement data. From the data collected during calendar year 2008, one week per month was randomly selected and processed to determine the mean placement location and standard deviation as a function of time of day and vehicle classification. The weekly data sets extracted from the database included information on vehicle classification, time of day, travel speed, and wheel placement offset within the outer travel lane. The placement offset of the front steering axle was used throughout this analysis.

Figures 8.3 and 8.4 illustrate the average weekly vehicle count and travel speed versus time of data, respectively, for this sample data set. As shown in Figure 8.3, the hourly vehicle counts peak between 11 am to 4 pm. The data in Figure 8.4 indicates the average travel speed is relatively consistent throughout the day, with the exception of a reduced period between 4 pm – 6 pm. Figures 8.5 and 8.6 illustrate the overall average and standard deviation of placement, respectively, versus time of day. As shown in Figure 8.5, placement offset values are relatively consistent between 6am – 6pm, with an average value of 34.1 inches, which is significantly higher than the default value of 18 inches used with the MEPDG software. Furthermore, the average offset values increase to approximately 42 inches between 6pm – 6am as traffic volumes decrease. An overall average placement offset of 35.5 inches was calculated from the data set of 566,184 vehicles, which included 95.6% cars and light trucks. The standard deviation of offset illustrated in Figure 8.6 indicate generally stable values ranging from a late evening / early morning low of 12.2 inches to a mid-day high of 14.1 inches. An overall standard deviation of 13.4 inches is calculated from this data sample.

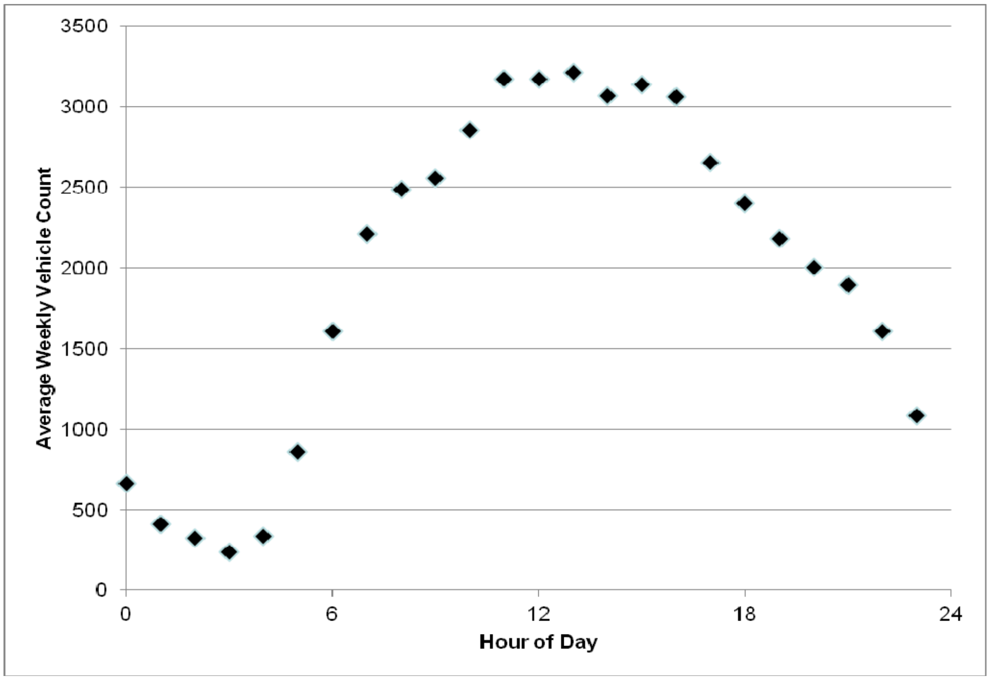


Figure 8.3: Outer Lane Average Weekly Vehicle Count Versus Time of Day, North-Leg of the Marquette Interchange

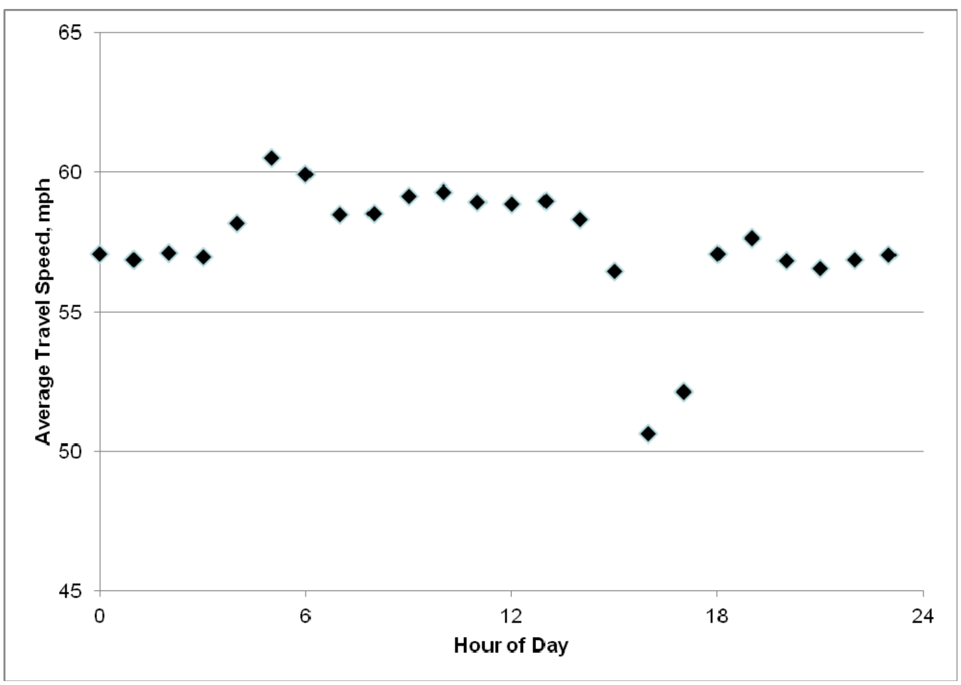


Figure 8.4: Outer Lane Average Travel Speed Versus Time of Day, North-Leg of the Marquette Interchange

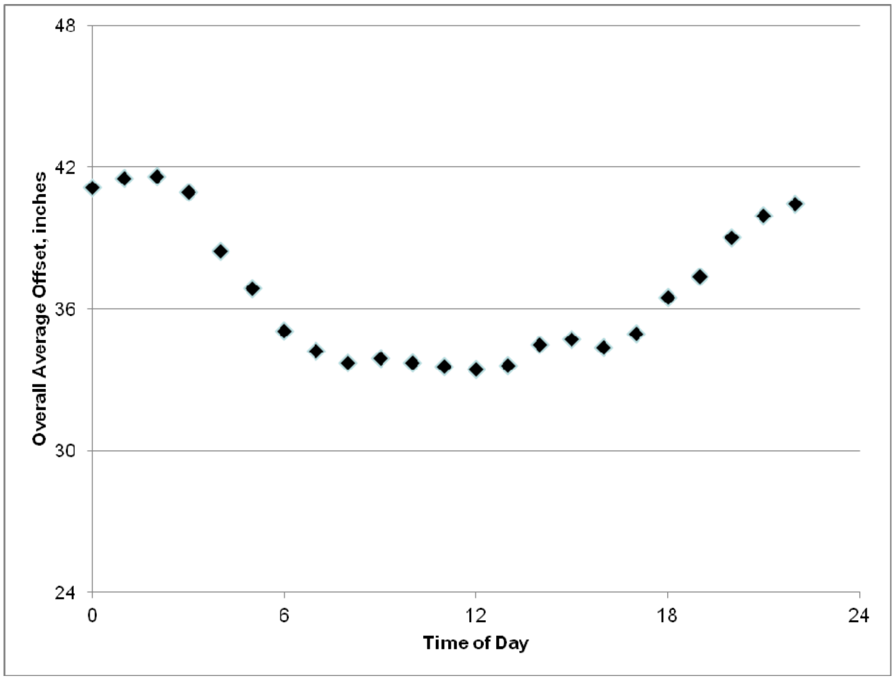


Figure 8.5: Outer Lane Average Placement Offset Versus Time of Day, North-Leg of the Marquette Interchange

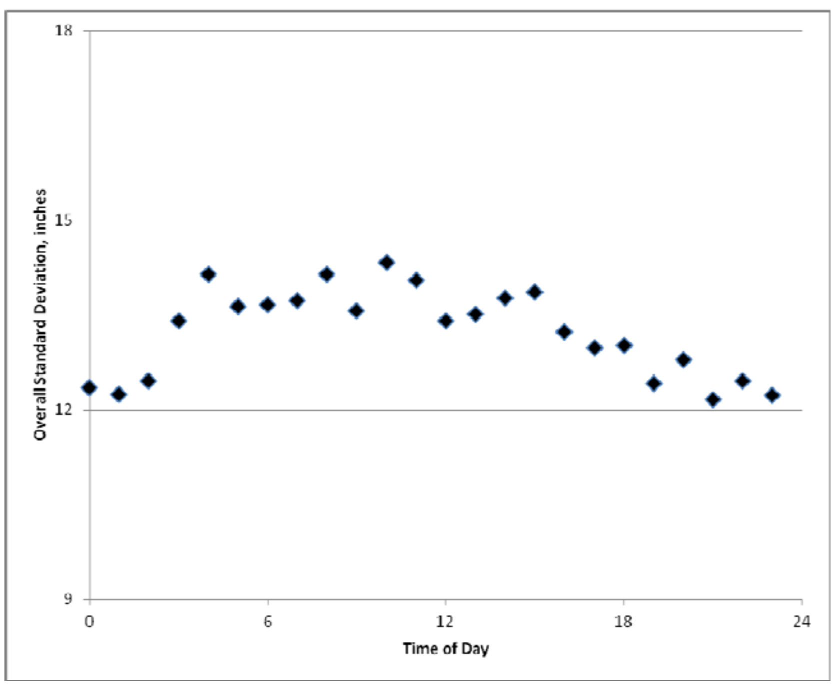


Figure 8.6: Outer Lane Standard Deviation of Placement Offset Versus Time of Day, North-Leg of the Marquette Interchange

The overall average and standard deviation of placement was analyzed based on FHWA vehicle classifications. Figure 8.7 provides a schematic illustration of the vehicle types included in each classification. For most pavement design purposes, only the heavy vehicles represented by classes 4 – 13 are considered. Figures 8.8 and 8.9 illustrate the overall average and standard deviation of placement, respectively, versus vehicle classification. As shown in Figure 8.8, placement offset values are relatively consistent for heavy trucks (FHWA Classifications 4 – 10). For this data, the overall average offset for the heavy trucks is 23.6 inches, which is close to the MEPDG default value of 18 inches. Figure 8.9 indicates the standard deviation of placement is consistent for all but class 6 and 7 vehicles, which represent 10% of the heavy trucks analyzed. For the class 6 and 7 vehicles, the standard deviation values are markedly greater than the remaining vehicle types. For all heavy trucks measured, the overall standard deviation of 14.8 inches is calculated from this data sample.

The analysis of placement data described above indicates a useful application for the type of data that may be collected using the wander and WIM strips. For this particular application, using site-specific values for average and placement variability would provide a more complete analysis of the expected pavement performance.

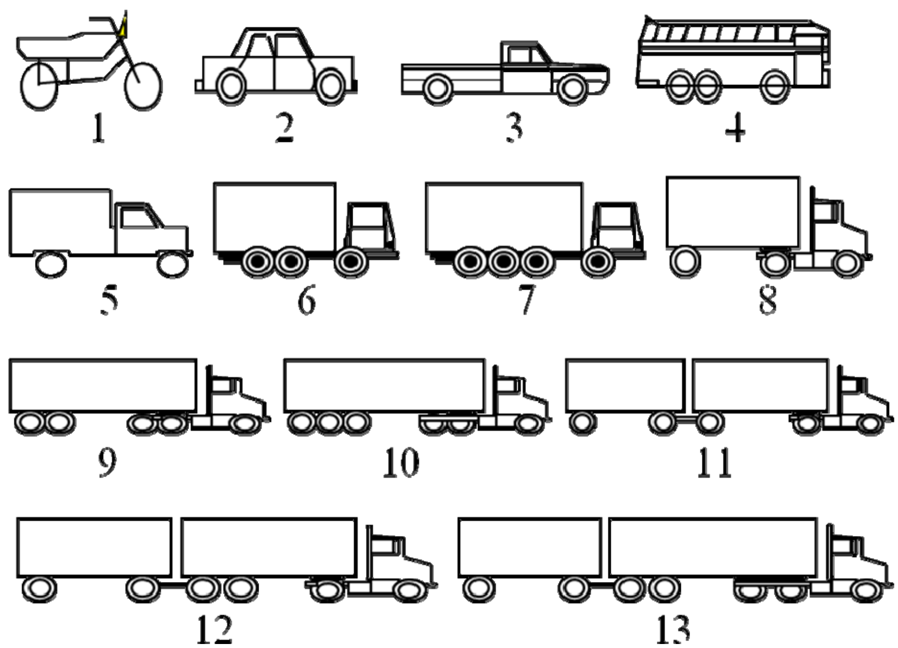


Figure 8.7: Schematic Illustration of FHWA Vehicle Classifications

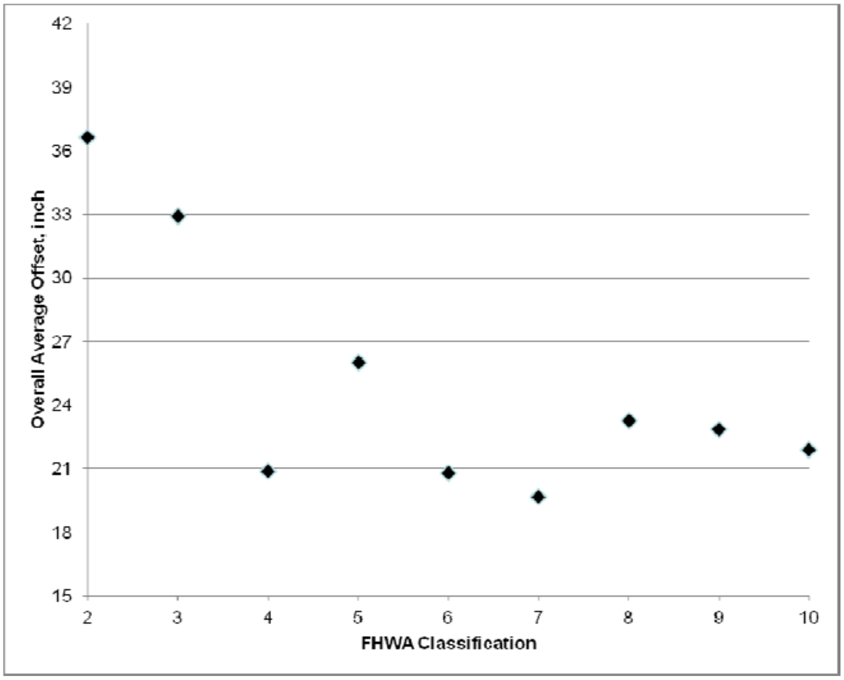


Figure 8.8: Wheel Offset Versus FHWA Vehicle Classification, North-Leg of the Marquette Interchange

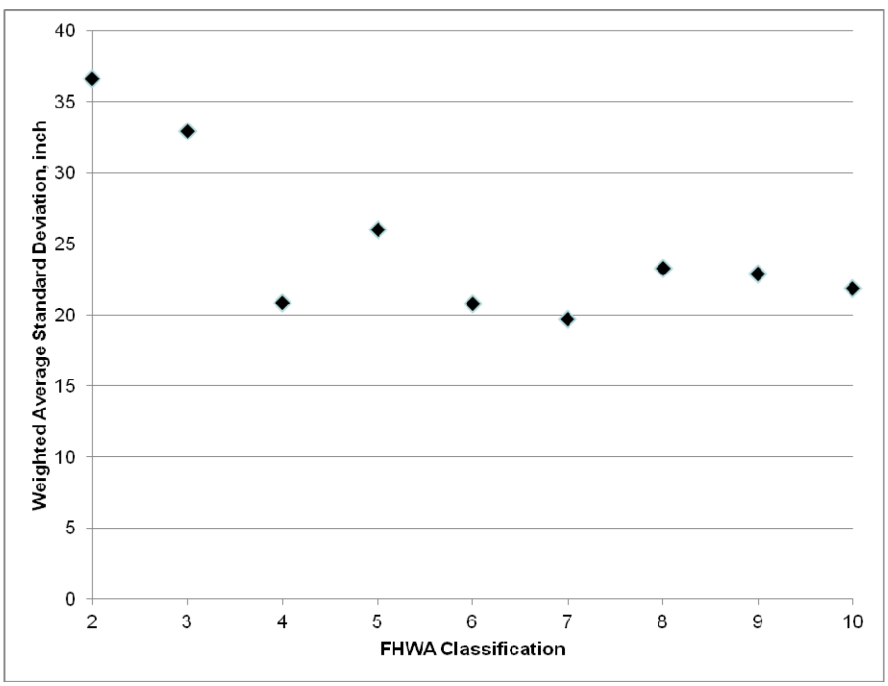


Figure 8.9: Standard Deviation of Wheel Offset Versus FHWA Vehicle Classification, North-Leg of the Marquette Interchange

8.3 Axle Spectra Analysis

A detailed mechanistic pavement design requires a thorough appraisal of the anticipated traffic loadings, including the vehicle class distribution, traffic growth factors and axle loading spectrum. The Marquette Interchange database includes detailed information on the axle loadings collected via the WIM system (i.e., quartz piezo strips and traffic loop) imbedded in the surface of the pavement. The database was queried to provide a sample data set to illustrate the development of traffic inputs for the mechanistic analysis. This data was supplemented with information available from the construction plans for the North-Leg of the Marquette Interchange, WisDOT State Project Number 1060-05-71.

The title sheet of the construction plans indicates the following:

1999 ADT = 138,800
2025 ADT = 152,700
2025 DHV = 11,800
Directional Distribution = 55/45
% Trucks = 11.0
Design Speed = 55 MPH
20 Year Design ESALs = 37,142,400

Using the above, the following mechanistic traffic inputs may be calculated:

Compound Growth Rate = 0.4%
2006 ADT = 142,000
2006 ADTT = 15,620

The period between June 13, 2007 and August 13, 2007 was randomly selected for analysis of collected WIM data to develop other needed traffic inputs. The database query yielded 114,817 vehicles, of which 4495 (3.9%) were heavy trucks (FHWA Class 4 – 12). This truck percentage is significantly lower that the design value of 11% due to traffic merge patterns upstream of the instrumented test location. Figures 8.10 and 8.11 illustrate example single and tandem axle load distributions, respectively, for vehicle classes 4, 6 and 9. From all of the processed data, tables of single, tandem, tridem and quad axle load distribution factors were developed for each truck class included in the data set (VC 4 – 12). These results are displayed in Tables 8.1 through 8.4. Additional inputs for mechanistic analysis include the percentage of truck by class and the average number of axles per truck. These values are provided in Tables 8.5 and 8.6, respectively.

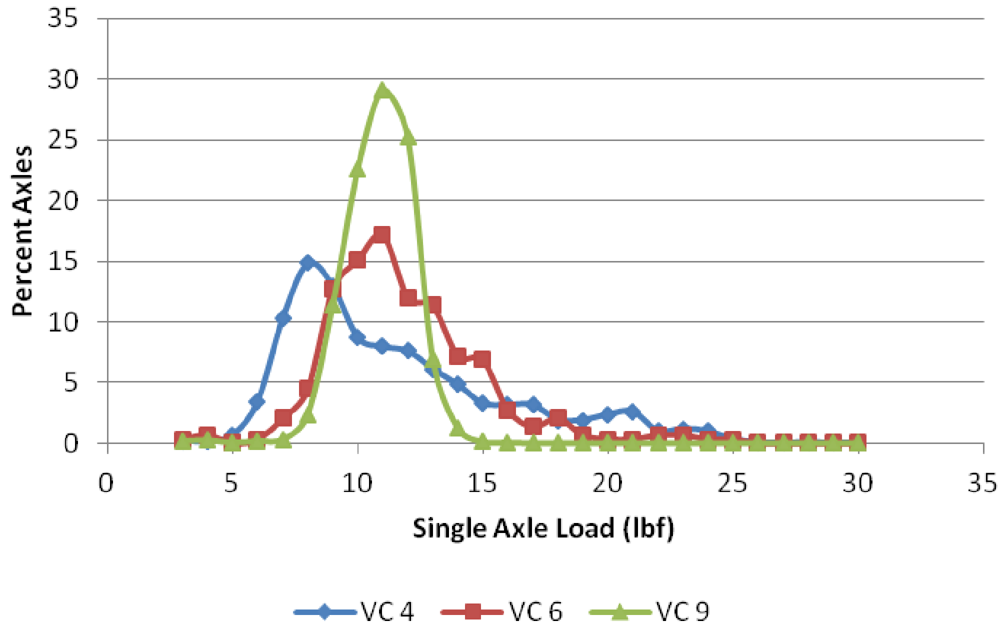


Figure 8.10: Single Axle Load Distribution for Class 4, 6 & 9 Trucks, North-Leg of the Marquette Interchange

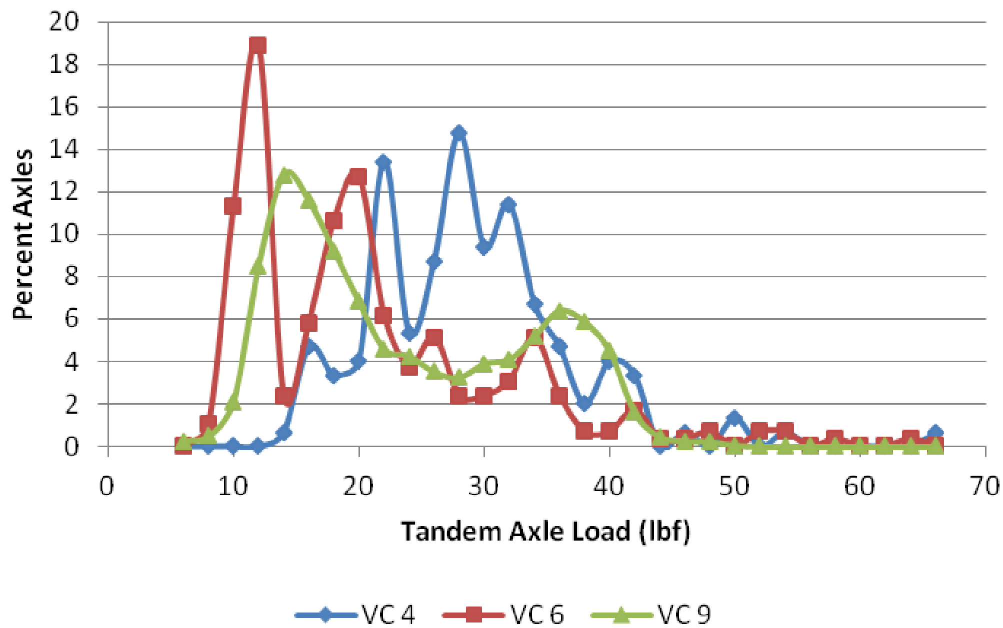


Figure 8.11: Tandem Axle Load Distribution for Class 4, 6 & 9 Trucks, North-Leg of the Marquette Interchange

Table 8.1: Single Axle Load Distribution Factors

Axle Load, lbf	**Truck Class**								
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
3000	0	1	0.5	0	2.9	0.1	0.1	4	0
4000	0.1	14.1	0.7	0	1.4	0.3	0	0	0
5000	0.7	10.6	0	0	0.3	0.1	0	4	5.7
6000	3.5	7.5	0.3	0	3.1	0.2	3.7	4	0
7000	10.3	13.3	2.1	0	6.5	0.3	0	0	6.3
8000	14.9	14.9	4.5	0.9	10.7	2.4	0	4	6.3
9000	13	10.6	12.7	1.9	14.6	11.4	3.7	12	6.3
10000	8.7	8	15.1	1.4	17.1	22.6	29.6	14	6.3
11000	8	5.7	17.2	1.4	12.4	29.1	33.3	12	6.3
12000	7.6	4.1	12	1.9	5.6	25.2	18.5	6	6.3
13000	6.1	2.3	11.3	4.7	5.9	6.9	7.4	6	6.3
14000	4.8	2	7.2	7.9	2.8	1.2	0	2	18.8
15000	3.3	1.3	6.9	9.8	2	0.1	0	6	0
16000	3.2	0.9	2.7	11.2	2.5	0.1	3.7	4	18.8
17000	3.2	0.9	1.4	6.5	2	0	0	4	0
18000	1.9	0.5	2.1	12.6	1.4	0	0	2	6.3
19000	1.9	0.5	0.7	10.3	2.8	0	0	4	6.3
20000	2.4	0.5	0.3	16.4	2.2	0	0	6	0
21000	2.6	0.4	0.3	6.5	0	0	0	6	0
22000	1	0.1	0.7	2.8	2	0	0	0	0
23000	1.2	0.3	0.7	2.8	0.6	0	0	0	0
24000	1	0.3	0.3	0.5	0.6	0	0	0	0
25000	0.3	0.2	0.3	0	0.3	0	0	0	0
26000	0.1	0	0	0.5	0	0	0	0	0
27000	0	0	0	0	0	0	0	0	0
28000	0.1	0	0	0	0	0	0	0	0
29000	0	0	0	0	0.3	0	0	0	0
30000	0.1	0	0	0	0	0	0	0	0
31000	0	0	0	0	0	0	0	0	0
32000	0	0	0	0	0	0	0	0	0
33000	0	0	0	0	0	0	0	0	0
Total	100	100	100	100	100	100	100	100	100

Table 8.2: Tandem Axle Load Distribution Factors

Axle Load, lbf	**Truck Class**								
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
6000	0	100	0	100	100	0.2	0	100	0
8000	0	0	1.1	0	0	0.5	0	0	0
10000	0	0	11.3	0	0	2.1	0	0	0
12000	0	0	18.9	0	0	8.5	7.5	0	0
14000	0.6	0	2.4	0	0	12.8	0	0	25
16000	4.7	0	5.8	0	0	11.6	7.4	0	0
18000	3.4	0	10.7	0	0	9.2	11.1	0	0
20000	4	0	12.7	0	0	6.8	3.7	0	25
22000	13.4	0	6.2	0	0	4.6	3.7	0	0
24000	5.4	0	3.8	0	0	4.3	0	0	0
26000	8.7	0	5.2	0	0	3.5	0	0	25
28000	14.8	0	2.4	0	0	3.2	3.7	0	25
30000	9.4	0	2.4	0	0	3.9	0	0	0
32000	11.4	0	3.1	0	0	4.1	3.7	0	0
34000	6.7	0	5.2	0	0	5.2	25.9	0	0
36000	4.7	0	2.4	0	0	6.4	14.8	0	0
38000	2	0	0.7	0	0	5.9	7.4	0	0
40000	4	0	0.7	0	0	4.5	3.7	0	0
42000	3.4	0	1.7	0	0	1.6	0	0	0
44000	0	0	0.3	0	0	0.5	3.7	0	0
46000	0.7	0	0.3	0	0	0.3	0	0	0
48000	0	0	0.7	0	0	0.2	0	0	0
50000	1.3	0	0	0	0	0.1	0	0	0
52000	0	0	0.7	0	0	0	0	0	0
54000	0.7	0	0.7	0	0	0	3.7	0	0
56000	0	0	0	0	0	0	0	0	0
58000	0	0	0.3	0	0	0	0	0	0
60000	0	0	0	0	0	0	0	0	0
62000	0	0	0	0	0	0	0	0	0
64000	0	0	0.3	0	0	0	0	0	0
66000	0.7	0	0	0	0	0	0	0	0
Total	100	100	100	100	100	100	100	100	100

Table 8.3: Tridem Axle Load Distribution Factors

Axle Load, lbf	**Truck Class**								
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
12000	100	100	100	0	100	100	18.6	100	100
15000	0	0	0	0	0	0	3.7	0	0
18000	0	0	0	0	0	0	7.4	0	0
21000	0	0	0	4	0	0	7.4	0	0
24000	0	0	0	0	0	0	3.7	0	0
27000	0	0	0	0	0	0	0	0	0
30000	0	0	0	11.5	0	0	7.4	0	0
33000	0	0	0	0	0	0	0	0	0
36000	0	0	0	15.4	0	0	0	0	0
39000	0	0	0	3.8	0	0	3.7	0	0
42000	0	0	0	15.4	0	0	14.8	0	0
45000	0	0	0	0	0	0	18.5	0	0
48000	0	0	0	19.2	0	0	11.1	0	0
51000	0	0	0	11.5	0	0	0	0	0
54000	0	0	0	11.5	0	0	0	0	0
57000	0	0	0	7.7	0	0	3.7	0	0
60000	0	0	0	0	0	0	0	0	0
63000	0	0	0	0	0	0	0	0	0
66000	0	0	0	0	0	0	0	0	0
69000	0	0	0	0	0	0	0	0	0
72000	0	0	0	0	0	0	0	0	0
75000	0	0	0	0	0	0	0	0	0
78000	0	0	0	0	0	0	0	0	0
81000	0	0	0	0	0	0	0	0	0
84000	0	0	0	0	0	0	0	0	0
87000	0	0	0	0	0	0	0	0	0
90000	0	0	0	0	0	0	0	0	0
93000	0	0	0	0	0	0	0	0	0
96000	0	0	0	0	0	0	0	0	0
99000	0	0	0	0	0	0	0	0	0
102000	0	0	0	0	0	0	0	0	0
Total	100	100	100	100	100	100	100	100	100

Table 8.4: Quad Axle Load Distribution Factors

Axle Load, lbf	**Truck Class**								
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
12000	100	100	100	0	100	100	100	100	100
15000	0	0	0	0	0	0	0	0	0
18000	0	0	0	0	0	0	0	0	0
21000	0	0	0	0	0	0	0	0	0
24000	0	0	0	0	0	0	0	0	0
27000	0	0	0	0	0	0	0	0	0
30000	0	0	0	0	0	0	0	0	0
33000	0	0	0	0	0	0	0	0	0
36000	0	0	0	1.1	0	0	0	0	0
39000	0	0	0	0.5	0	0	0	0	0
42000	0	0	0	0.5	0	0	0	0	0
45000	0	0	0	1.1	0	0	0	0	0
48000	0	0	0	2.7	0	0	0	0	0
51000	0	0	0	3.7	0	0	0	0	0
54000	0	0	0	6.9	0	0	0	0	0
57000	0	0	0	8	0	0	0	0	0
60000	0	0	0	16.5	0	0	0	0	0
63000	0	0	0	22.3	0	0	0	0	0
66000	0	0	0	13.8	0	0	0	0	0
69000	0	0	0	11.7	0	0	0	0	0
72000	0	0	0	6.4	0	0	0	0	0
75000	0	0	0	2.1	0	0	0	0	0
78000	0	0	0	1.6	0	0	0	0	0
81000	0	0	0	0	0	0	0	0	0
84000	0	0	0	1.1	0	0	0	0	0
87000	0	0	0	0	0	0	0	0	0
90000	0	0	0	0	0	0	0	0	0
93000	0	0	0	0	0	0	0	0	0
96000	0	0	0	0	0	0	0	0	0
99000	0	0	0	0	0	0	0	0	0
102000	0	0	0	0	0	0	0	0	0
Total	100	100	100	100	100	100	100	100	100

Table 8.5: Truck Class Distribution

Truck Class	**Truck Count**	**% of Total**
4	882	19.5
5	1396	31.1
6	291	6.5
7	214	4.8
8	147	3.3
9	1524	33.9
10	27	0.6
11	10	0.2
12	4	0.1
13	0	0
Total	**4495**	**100**

Table 8.6: Average Number of Axles/Truck

Truck Class	**Axle Type**			
	Single	**Tandem**	**Tridem**	**Quad**
4	1.83	0.17	0	0
5	2	0	0	0
6	1	1	0	0
7	1	0	0.12	0.88
8	2.42	0.58	0	0
9	1	2	0	0
10	1	1	1	0
11	5	0	0	0
12	4	1	0	0
13	3	2	0	0

8.4 Piezo Strip Analysis

During the active period of WHRP Project 0092-06-01, the raw signals from the quartz piezo strips were not available for analysis due to manufacturer restrictions for the weigh in motion (WIM) system. As indicated earlier, the Project 0092-06-01 also utilized traditional PK piezo strips to characterize traffic wander patterns. An analysis of the signals from these lower cost PK piezo strips was conducted to determine if accurate axle load measurements could be obtained, thus significantly lowering the cost for installation and maintenance of a WIM system integrated into infrastructure health monitoring sites.

To better understand the behavior of the quartz and PK piezo strips, the Marquette Interchange data collection hardware was re-engineered to provide complete signal traces for both the traditional PK and quartz piezo strips. These traces were analyzed to determine the area beneath the signal for individual wheel loadings, with the area ratio between the PK and quartz piezo strips being used for comparative purposes. Because the quartz piezo strips are considered acceptable for accurately measuring applied wheel loads, if the area ratio between strip types is stable for the anticipated range of wheel loadings, these lower cost PK strips could be used as integral parts of WIM systems deployed as needed.

Figure 8.12 provides an example trace from two traditional PK and two quartz piezo strips resulting from a two axle vehicle passage, collected in December 2011. PK1 is positioned perpendicular to the traffic direction and PK2 is positioned at a slight angle to traffic (See Figure 8.1). Both quartz strips are positioned perpendicular to traffic. As shown, the voltage change recorded by the quartz strips is substantially greater than that recorded by the PK strips. Even though the actual weights of these two wheel loadings are unknown, it follows that the weight of each wheel is unchanged as the wheel travels across each strip and that the area beneath the pulses is proportional to the applied loading. Analysis of the quartz piezo strips indicates the area ratio (quartz 1 / quartz 2) for the front and rear wheel loads is 1.06 and 1.02, respectively. The area ratios for each individual strip (wheel 1 / wheel 2) are computed as 1.41 and 1.36 for Quartz strips 1 and 2, respectively. These ratios indicate the quartz strips are in general agreement and that wheel load 1 is approximately 40% greater than wheel load 2.

The area ratios for each traditional PK1 strip (wheel 1 / wheel 2) are computed as 0.64 and 1.69 for PK strips 1 and 2, respectively, which indicate significantly more variability than the values computed for the quartz strips. The wheel 1 area ratios for the quartz and PK strips (quartz 1 / PK) are computed as 4.67 and 3.67 for PK strips 1 and 2, respectively. The wheel 2 area ratios for the quartz and PK strips (quartz 1 / PK) are computed as 2.18 and 4.42 for PK strips 1 and 2, respectively. Again these ratios indicate significantly more variability for the PK strips.

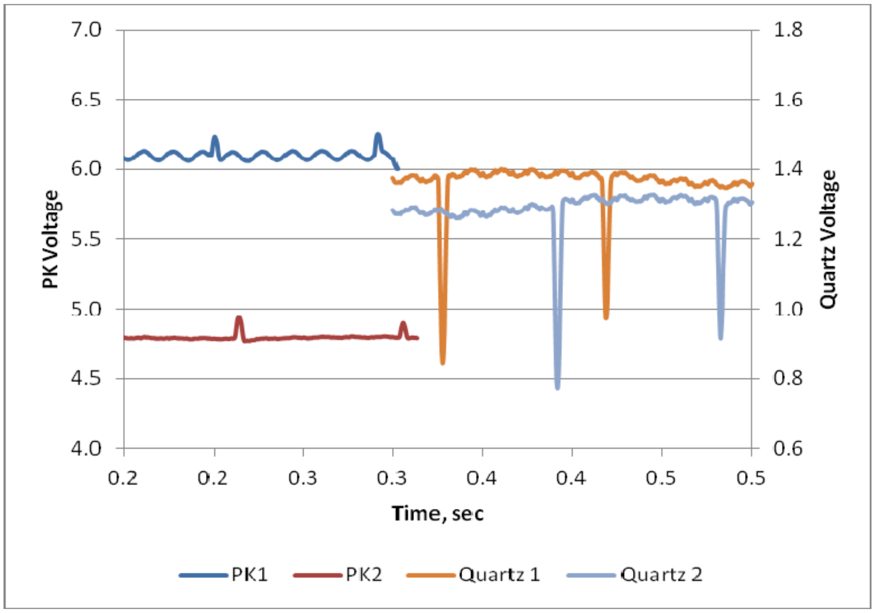


Figure 8.12: Example voltage traces for PK and Quartz piezo strips (December 2011)

The re-engineered data collection system was used to capture wheel loading events for a 1-week period from January 30, 2012 to February 5, 2012. A total of 86,900 vehicle passages were recorded, with the steering axle passage being preserved for analysis. A computational algorithm was developed to identify the beginning and ending points for each voltage pulse and the area beneath each pulse curve. A time stamp was also determined for each voltage pulse. From the time stamps, travel speeds were computed from both the PK and quartz sensor strips. The placement offset was also calculated from the PK time stamps.

An initial review of the computational results indicated that PK Sensor 3 and Quartz Sensor 2 were providing erratic results. The raw data was then filtered based on the following criteria:

1. Placement offset between 41 and 63 inches, thus isolating Quartz 3 and Quartz 4
2. The ratio of speeds calculated by the PK and Quartz sensors between 0.8 and 1.2
3. The ratio of areas calculated for Quartz 3 and Quartz 4 between 0.8 and 1.2

After filtering, a total of 32,926 loading events remained. From these events, the areas beneath the PK and Quartz sensor pulses were compared to assess the validity of using the PK sensors in place of the Quartz sensors for WIM applications.

Figures 8.13 and 8.14 provide example comparison plots between Quartz sensor 3 and PK sensors 1 and 2, respectively. As shown, there is a strong relationship between the areas beneath the Quartz and PK sensors, with significantly more scatter for the angled PK sensor 2. Table 8.7 provides summary statistics for the PK and Quartz sensor analyses.

Table 8.7: Summary Statistics for PK and Quartz Strip Comparisons (n=32,926)

Comparison	Max	Min	Avg.	Std Dev	COV, %
Offset2	63.0	41.0	51.5	5.94	11.5
PK Speed	85.7	20.1	58.5	5.16	8.8
Quartz speed	82.2	19.5	57.1	4.94	8.7
Q/PK Speed Ratio	1.1	0.9	1.0	0.02	1.6
Q4/Q3 Area Ratio	1.2	0.8	0.9	0.05	6.0
PK1/Q3 Area Ratio	1.1	0.1	0.3	0.02	7.4
PK2/Q3 Area Ratio	0.6	0.1	0.2	0.03	16.0
PK1/Q4 Area Ratio	1.0	0.1	0.3	0.03	7.8
PK2/Q4 Area Ratio	0.6	0.1	0.2	0.03	14.6
PK1/PK2 Area Ratio	4.6	0.8	1.7	0.29	17.3

As shown in Table 8.7, the comparisons between PK1 and Quartz 3 and 4 have coefficients of variation (COV) similar to the Quartz 4/3 comparison, indicating that this strip type/configuration may be a suitable replacement for structural health monitoring WIM applications. However, more research and testing is needed to determine if these promising relationships are stable over a broader range of loadings and ambient temperatures.

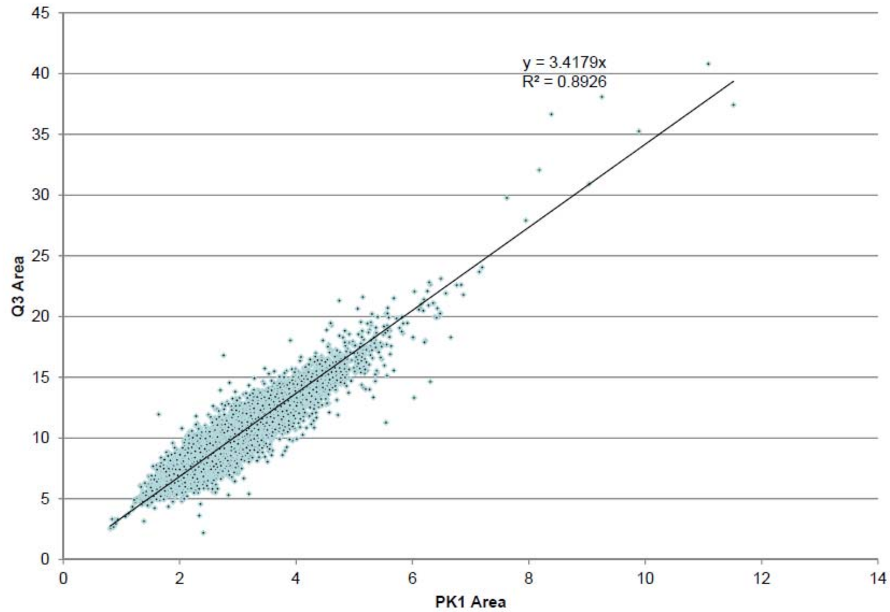


Figure 8.13: Comparison Between Quartz 3 and PK 1 sensors

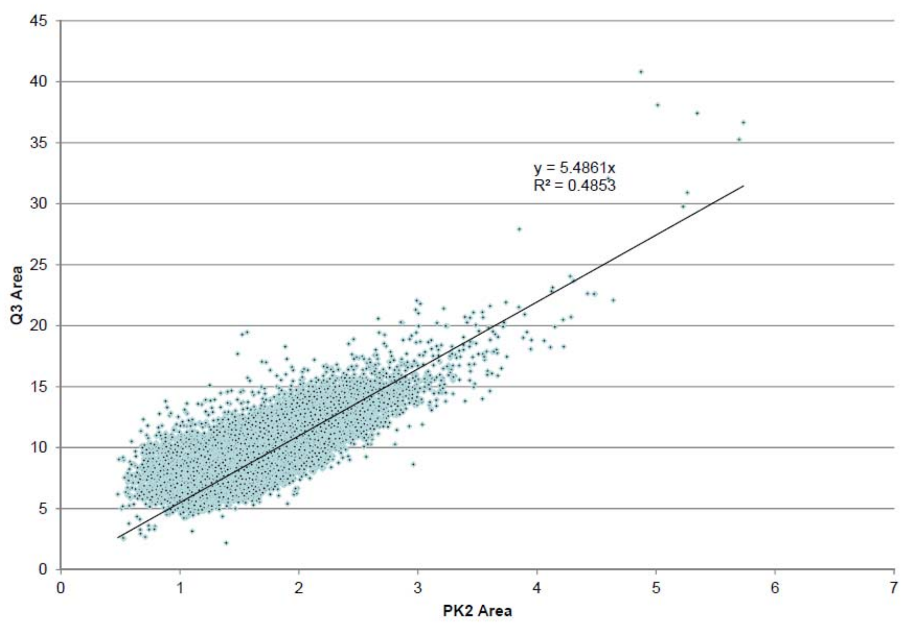


Figure 8.14: Comparison Between Quartz 3 and PK 2 sensors

8.5 Analysis of Pavement Performance Utilizing Data Collected from Instrumented Marquette Interchange Pavement Section

The American Association of Highway and Transportation Officials (AASHTO) developed DARWin-ME™ as next generation pavement design software that is based on Mechanistic-Empirical principles. With this new design methodology and software the pavement design moves away from a nomograph-based design to one that can predict multiple performance indicators and that will provide a direct tie between materials, structural design, construction, climate, traffic, and pavement management systems.

Available data on traffic, climate and materials from the Marquette Interchange project was used together with some defaults values to analyze a pavement section with DARWin-ME™.

The first step to be taken to start analyzing the pavement section is to input all data necessary regarding traffic, climate and materials but before doing that the general information of the project, performance criteria and reliability level needs to be defined.

The Marquette Interchange project is composed of a new flexible pavement that in the case of this report was analyzed for a period of 20 years. The performance criteria are designer selected critical limits or threshold values that could be represented by agency policies. The performance criteria critical limits and reliability level used, in the specific case of this analysis, were the default values from the software that were determined with the Long Term Pavement Performance (LTPP) data.

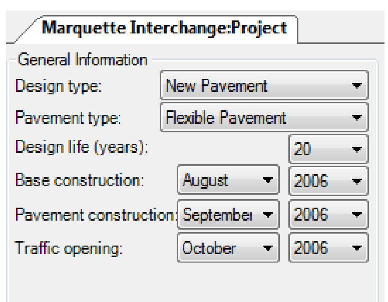


Figure 8.15: Marquette Interchange project general information

Performance Criteria	Limit	Reliability
Initial IRI (in./mile)	63	
Terminal IRI (in./mile)	172	90
AC top-down fatigue cracking (ft/mile)	2000	90
AC bottom-up fatigue cracking (percent)	25	90
AC thermal fracture (ft/mile)	250	90
Permanent deformation - total pavement (in.)	0.75	90
Permanent deformation - AC only (in.)	0.25	90
Reflective cracking (percent)	100	50

Figure 8.16: Performance Criteria

Traffic data available for the Marquette Interchange consists of two-way AADTT, number of lanes, percent truck in design direction and design lane and operational speed. Defaults values were used for data on axle load configuration, lateral wander and wheelbase. Data on vehicle class distribution and growth, axles per truck and axle load spectra distribution for single, tandem, tridem and quad axles was also available and imported to the software.

For the mechanistic-empirical pavement design methodology detailed climatic data are required for predicting pavement distress. This includes hourly temperature, precipitation, wind speeds, relative humidity, and cloud cover. All this climate data needed by the mechanistic-empirical method are available from weather stations around the United States. The DARWin-ME^{TM} software has an extensive number of stations embedded for ease of use and implementation and in the specific case of this analysis the station from Milwaukee, WI was used.

The pavement structure of the Marquette Interchange project consists of 8 different layers. The first 3 layers are Hot Mix Asphalt Concrete (HMAC) layers composed of a 2 inches 12.5 mm Stone Matrix Asphalt (SMA) wearing surface, a 7 inches 19.0 mm E30x Hot Mix Asphalt (HMA) and a 4 inches 19.0 mm C2 HMA. Two different types of asphalt binder were used for this project. For the wearing surface a PG 70-22 binder was used and for the second and third layer a PG 64-22 binder was used. Superpave ® test data that includes complex shear modulus (G*) and phase angle (°) for both binders grades and HMA mechanical properties that includes laboratory measured dynamic modulus was available. Default values for the mixtures volumetric properties were used and the Indirect Tensile Strength and Creep Compliance were calculated internally by the software using correlations. For the thermal properties of the mixture, that includes thermal conductivity and heat capacity, default values were used.

Figure 8.17: Marquette Interchange pavement material layers

Three different layers underneath the AC layers composed the base of the project. First, is a 4 inches open graded aggregate layer and under this layer there is a 6 inches dense graded aggregate layer and an 18 inches selected crushed aggregate layer. Data regarding gradation, plasticity index, liquid limit, maximum dry unit weight, optimum gravimetric water content and resilient modulus for these 3 layers was available and used in the analysis. Default values for Poisson’s ratio and coefficient of lateral earth pressure were selected.

The subgrade of this project consisted of 12 inches of A-4 soil and the remaining of the soil underneath the top 12 inches of soil. Data regarding gradation, plasticity index, liquid limit, maximum dry unit weight, saturated hydraulic conductivity, optimum gravimetric water content, and resilient modulus for these 2 layers was available and used in the analysis. Default values for Poisson's ratio and coefficient of lateral earth pressure were selected.

After inputting all the required data the analysis can be run and a report will be generated by the software. The generated report consists of a summary of the design inputs, design outputs, traffic inputs, climate inputs and design properties of the project.

For example the design output consists of the distress prediction summary and the distress charts. As mentioned previously the software predicts multiple performance indicators and these can be studied from the distress prediction summary and charts generated by DARWin-ME™.

For the Marquette Interchange project the 20 years analysis shows that the pavement will fail for terminal International Roughness Index (IRI), permanent deformation for the total pavement and for the AC only and also fails for AC top-down fatigue cracking.

Design Outputs

Distress Prediction Summary

Distress Type	Distress @ Specified Reliability		Reliability (%)		Criterion Satisfied?
	Target	Predicted	Target	Achieved	
Terminal IRI (in./mile)	172.00	181.01	90.00	84.80	Fail
Permanent deformation - total pavement (in.)	0.75	1.00	90.00	27.37	Fail
AC bottom-up fatigue cracking (percent)	25.00	1.45	90.00	100.00	Pass
AC thermal fracture (ft/mile)	250.00	27.17	90.00	100.00	Pass
AC top-down fatigue cracking (ft/mile)	2000.00	13803.32	90.00	0.03	Fail
Permanent deformation - AC only (in.)	0.25	0.45	90.00	22.54	Fail

Figure 8.18: Distress prediction summary estimated by DARWin-ME™

As shown in the previous figure when comparing the target distress with the predicted distress at the specified reliability it can be observed that for the cases of the terminal IRI and permanent deformation the target and the predicted do not differ much from each other. When comparing AC top-down fatigue cracking target and predicted distresses it can be noticed that the predicted distress is almost 7 times higher than the target distress. With these results is obvious that the most critical distress for this project is the AC top-down fatigue cracking.

Also by analyzing the distress charts the year in which the predicted distresses exceed the target distress can be determined. In the case of predicted IRI and rutting it can be seen that they exceed the target distress at the specified reliability around the 17 and 7 year, respectively. In the case of predicted AC top-down cracking, which was identify as the most critical distress according to the distress prediction, it can be observed that by year one the target distress will be exceed by the predicted distress. A common solution to this type of distress will be to mill and replace the wearing surface.

Something that is important to mention regarding the mechanistic-empirical design methodology is that using the default calibration factors for the models underpredicts the performance and for new pavement analysis the rutting is over predicted. These were notes taken at the 91st Annual Meeting of the Transportation Research Board (TRB) DARWin-ME™ workshop.

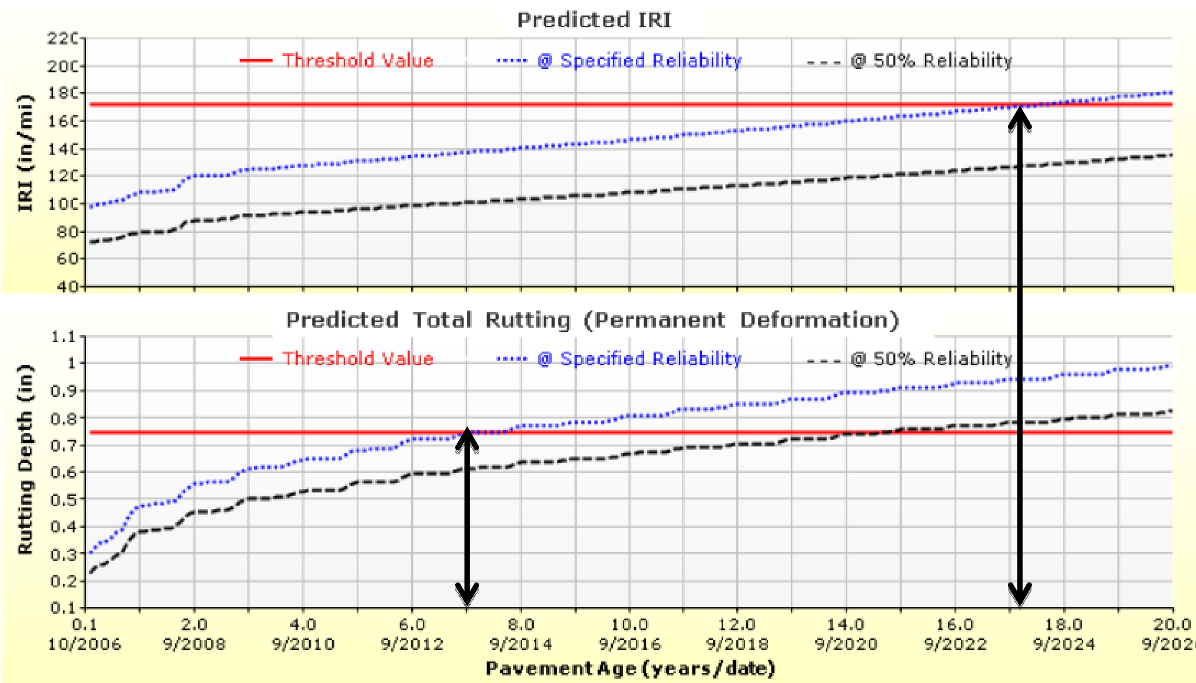


Figure 8.19: Predicted IRI and Total Rutting charts generated by DARWin-ME™

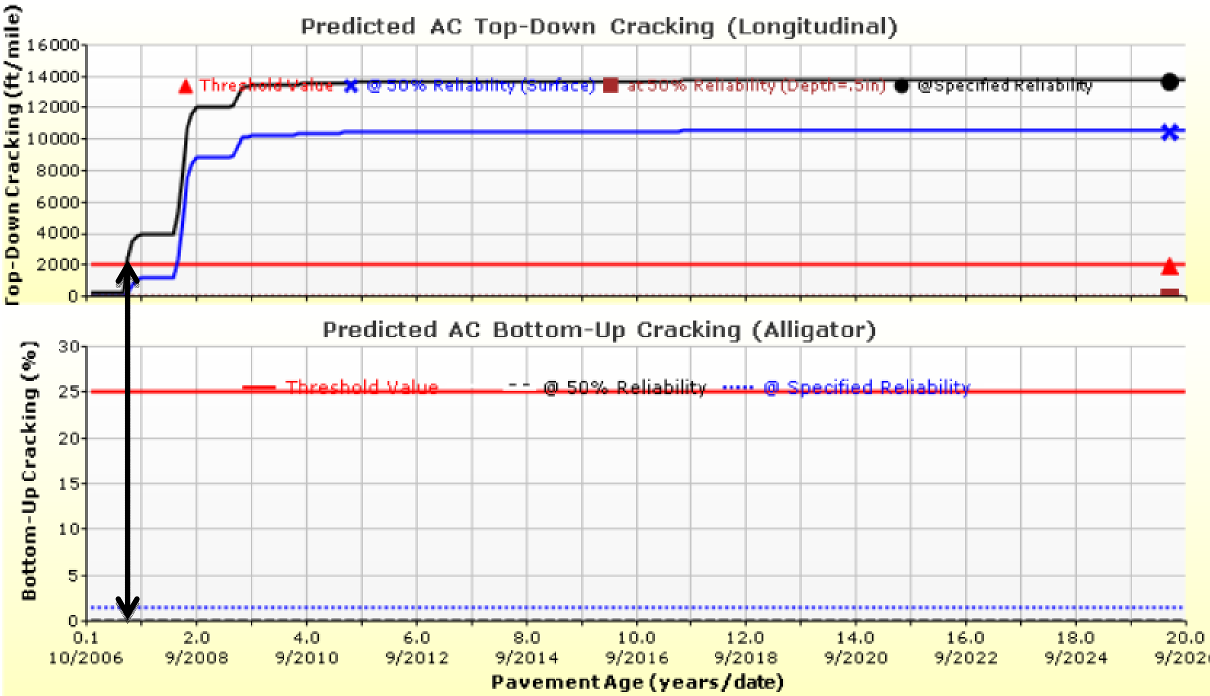


Figure 8.20: Predicted AC Top-Down and Bottom-Up cracking charts generate by DARWin-ME™

Chapter 9

Infrastructure Health Monitoring Survey

This presents the results of a survey conducted to obtain the state of the practice on infrastructure health monitoring implementation by highway agencies in the U.S. and Canada. Survey results are analyzed and evaluated.

9.1 Conducting the IHM Survey

The research team designed the IHM survey with various questions to obtain the current state of practice of highway agencies in the U.S. and Canada. The survey questions are presented in Appendix A.

The research team conducted the survey by e-mail and phone calls after contacting each highway agency to identify engineers who can answer the survey questions. Conducting the survey was challenging and effort demanding. In some cases, it was not possible for one engineer to answer the survey questions and we were directed to contact other engineers within the same highway agency.

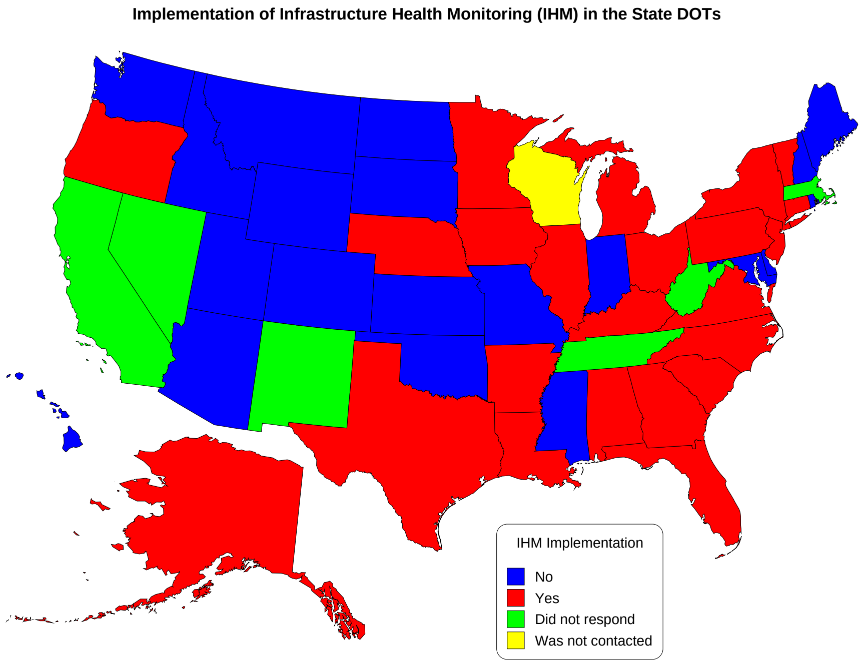
Forty nine State DOTs in the U.S. and 13 Ministries of Transportation (MOTs) in Canada were contacted to answer the survey questionnaire. Out of the 49 State DOTs, six agencies did not respond to the request of the research team (California, Massachusetts, Nevada, New Mexico, Tennessee and West Virginia). All Canadian MOTs submitted answers to the survey questionnaire.

9.2 Analysis of the IHM Survey of State DOTs, U.S.

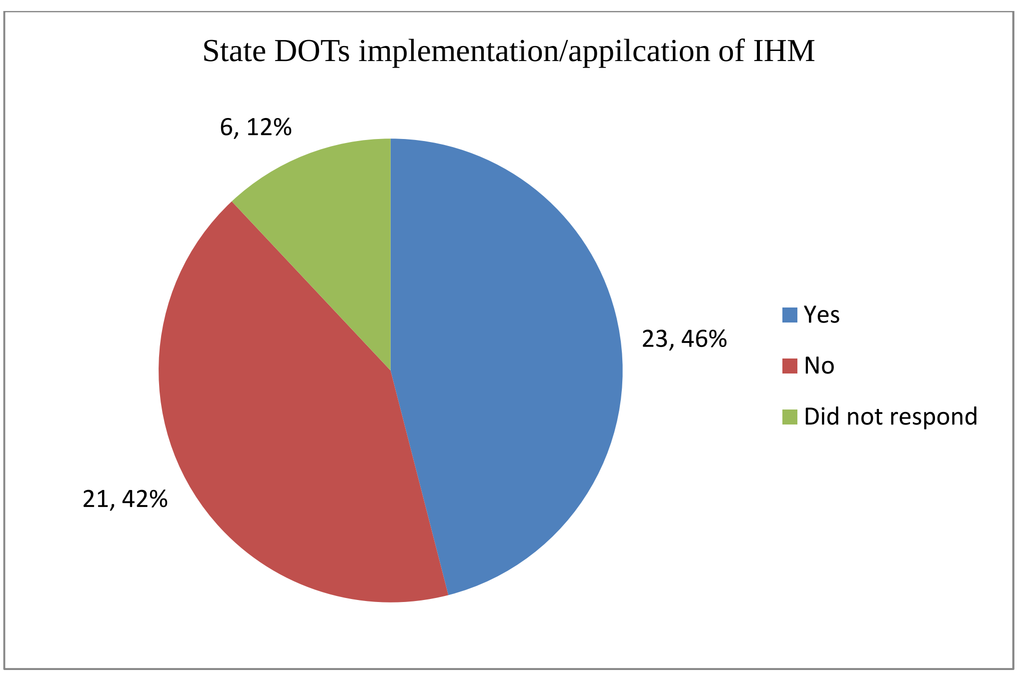
Forty four State DOTs answered the survey questionnaire. The answers and collected information were compiled into spreadsheet files to facilitate data analysis and presentation in graphical format. In addition, the answers were analyzed using Map Viewer software in order to present the individual State DOT response to the survey questions.

When asked about health monitoring applications for transportation infrastructure that have been implemented or are currently being implemented by State DOTs, 46% of State DOTs answered yes and 42% of State DOTs answered no (since there were 12% of State DOTs did not respond).

The results are depicted in Figure 9.1 in a map as well as pie chart format. Few engineers at the State DOTs with the answer "No," indicated that their agencies are interested in the subject and they will be looking into this in the near future.



(a) Map representation



(b) Pie chart representation

Figure 9.1: Current status for implementing IHM applications by State DOTs in the U.S.

State DOTs with current applications of IHM systems focus on bridges and pavements more than any other categories of transportation infrastructure. As shown in Figure 9.2, 51% of State DOTs implemented IHM applications for bridges, 16% for pavements, 9% for slopes, and 7% for structures of traffic control devices (sign structures). Figures 9.3 and 9.4 depict maps of the states that implemented IHM for bridges and pavements, respectively.

The state highway agencies with the answer “other” provided the following:

- Sink holes and water table measurement
- Systems connected vehicle test beds for safety, mobility, air quality, and asset management initiatives

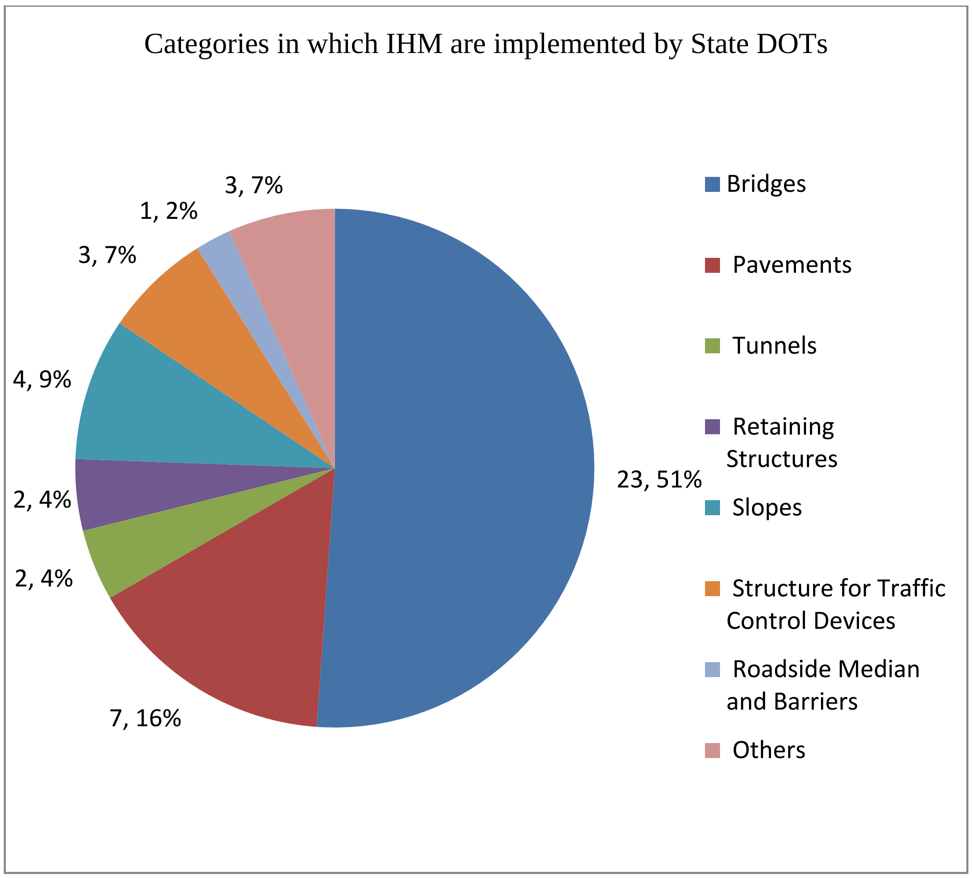


Figure 9.2: Categories of transportation infrastructure subjected to health monitoring applications by State DOTs

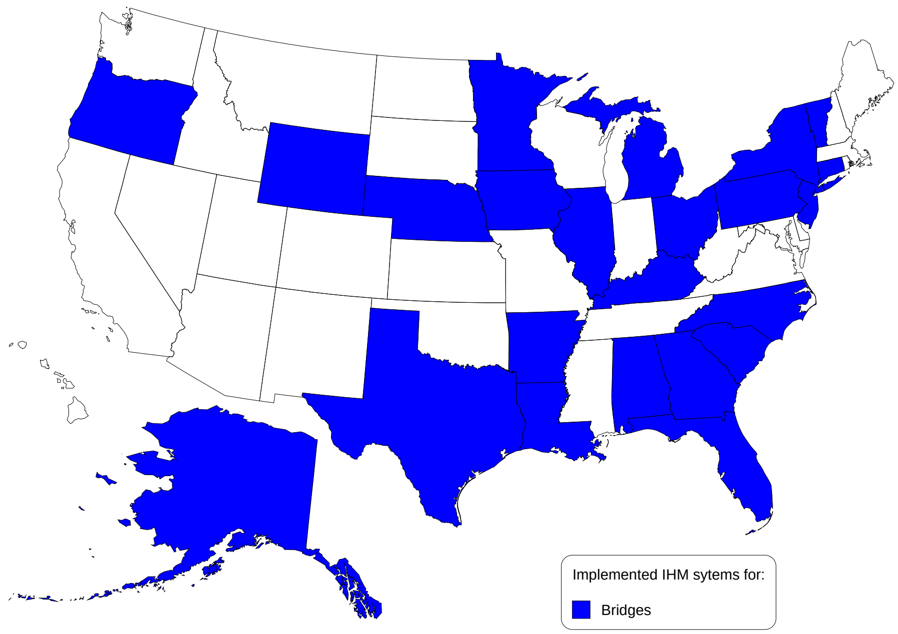


Figure 9.3: Maps of States with DOTs implementing IHM systems for bridge structures

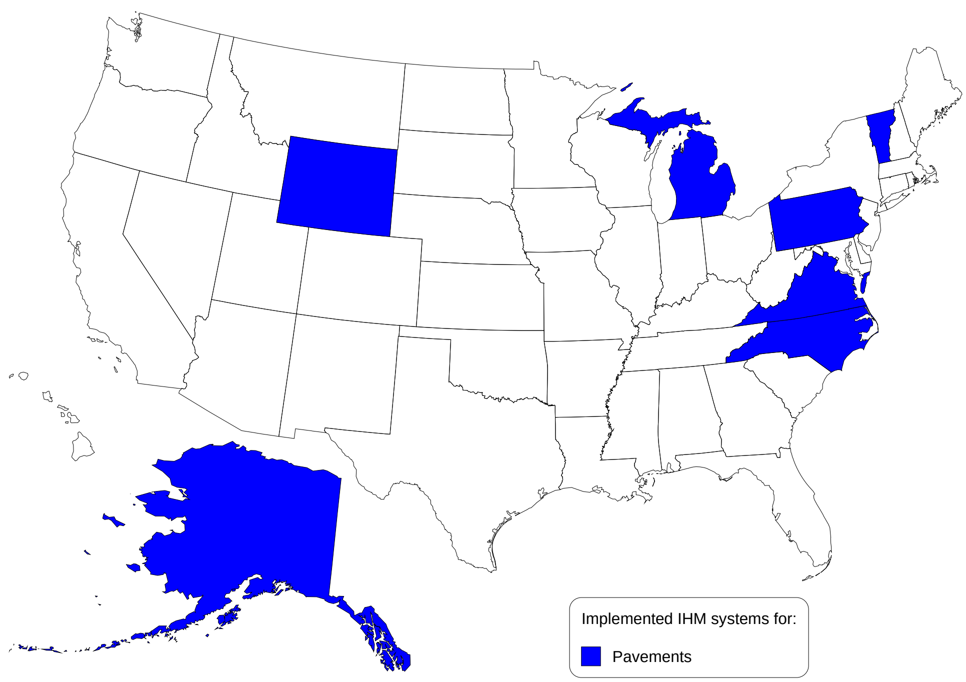


Figure 9.4: Maps of States with DOTs implementing IHM for pavements.

The primary objectives for State DOTs who have IHM applications/implementations include: identification of critical structural or safety conditions (41% of State DOTs), support infrastructure maintenance planning (25% of State DOTs), and reduce manual data collection (16% of State DOTs). The results are presented graphically in Figure 9.5.

Figures 9.6 and 9.7 present maps of the states with IHM objectives of identification of critical structural or safety conditions and support infrastructure maintenance planning, respectively.

State highway agencies with the answer "other" gave the following:

- Research project test concept, monitor cathodic protection devices
- Research implementation of IHM
- Development of rating information for marginal structures
- Evaluate design methodology and long term monitoring the structural health of the bridge
- Assist with design decision making

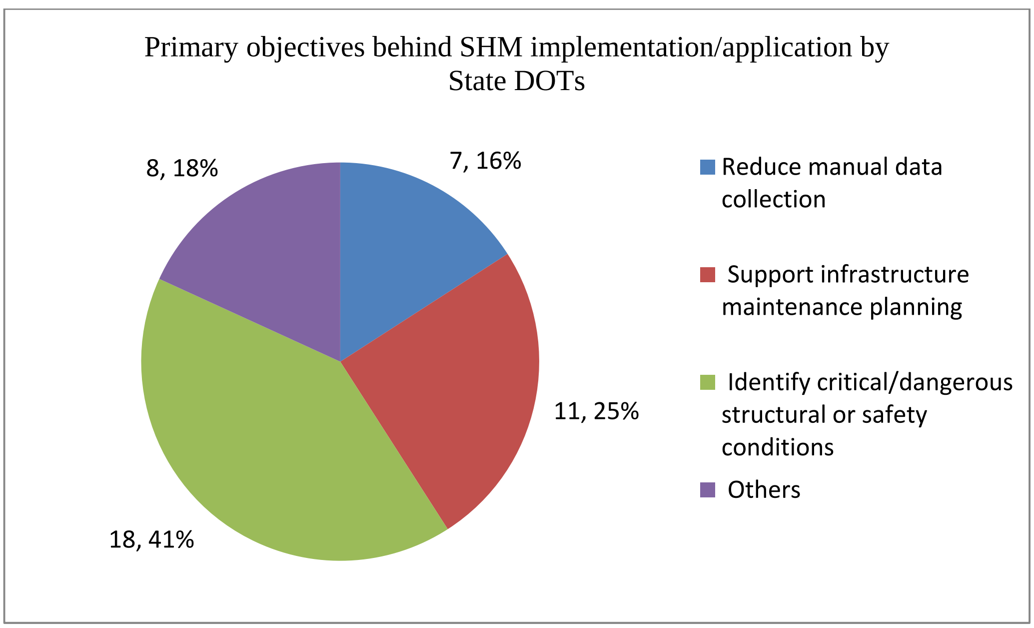
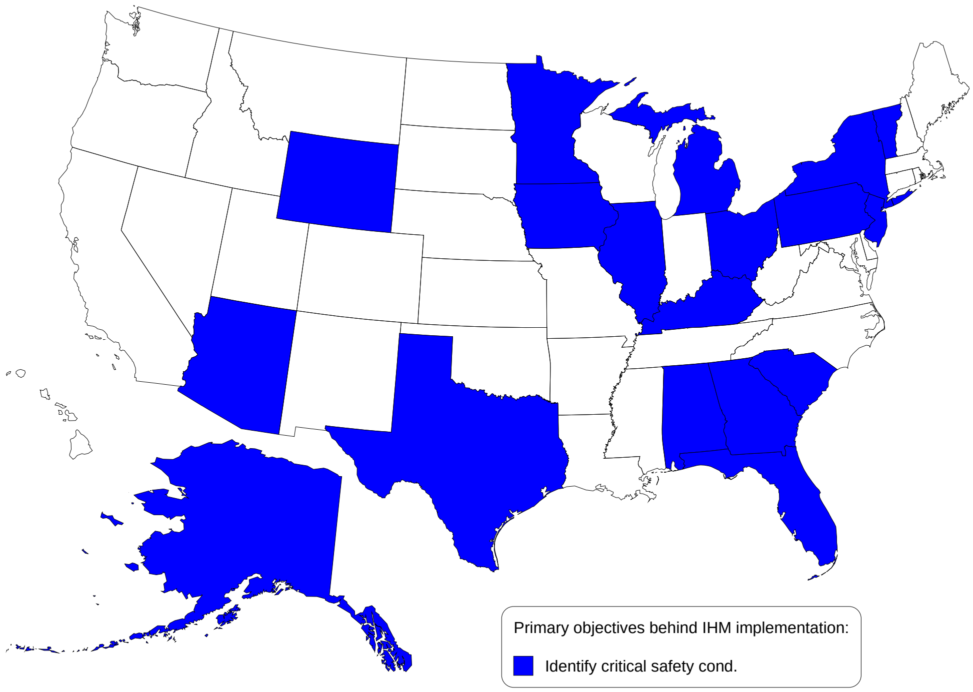


Figure 9.5: Response of State DOTs on the primary objectives behind your SHM implementation/application



Figures 9.6: Maps of the states with IHM objective of identification of critical structural or safety conditions

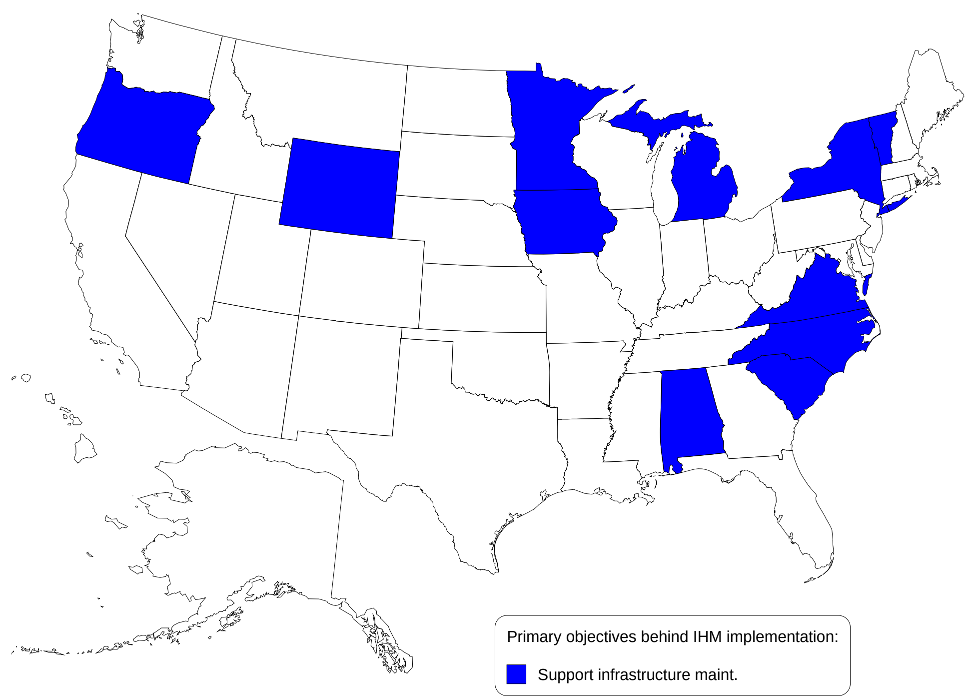


Figure 9.7: Maps of the states with IHM objective of support infrastructure maintenance planning.

Since majority of IHM applications reported are directed toward bridge structures as indicated by Figures 9.2 and 9.3, strain/deflection, tilt, vibrations, load/pressure, and thermal effects are the main data elements collected by State DOTs who implemented IHM systems, as depicted in Figure 9.8.

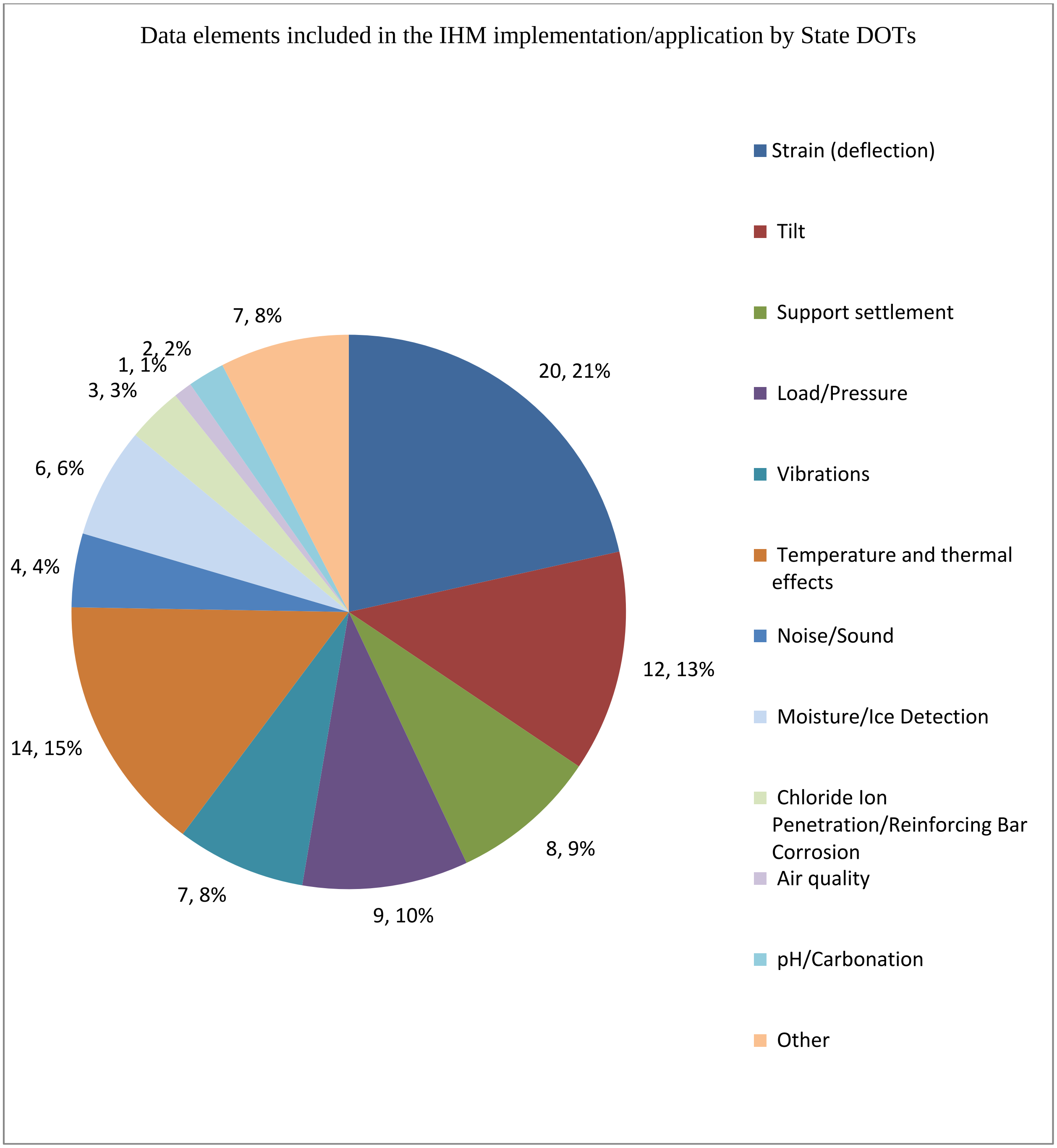


Figure 9.8: Data elements collected by State DOTs who implemented IHM systems.

State highway agencies with the answer "other" provided the following:

- Stream scour under bridges
- Pressure cells, accelerometers, corrosion sensors
- Weigh in motion, vehicle speed, GPS, direction, weather, and pavement quality.

Figure 9.9 and 9.10 show maps of the states with DOTs measuring stain/deflection and monitoring temperature and thermal effects, respectively.

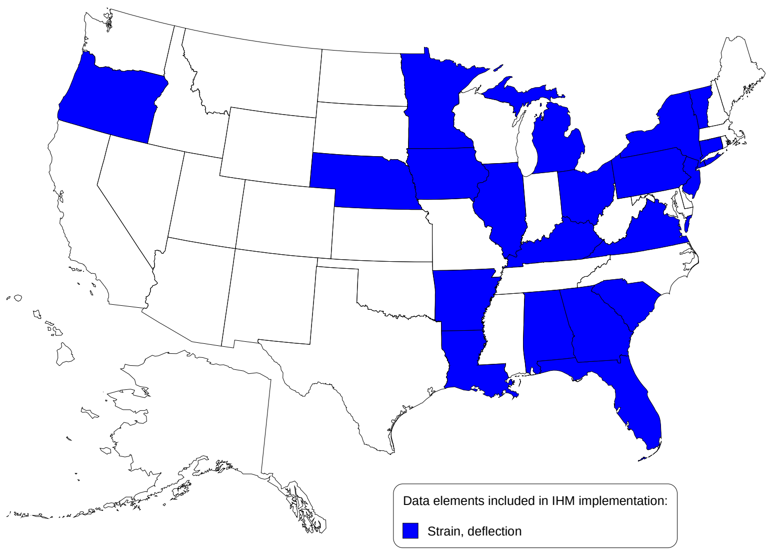


Figure 9.9: Maps of the states with DOTs measuring stain/deflection.

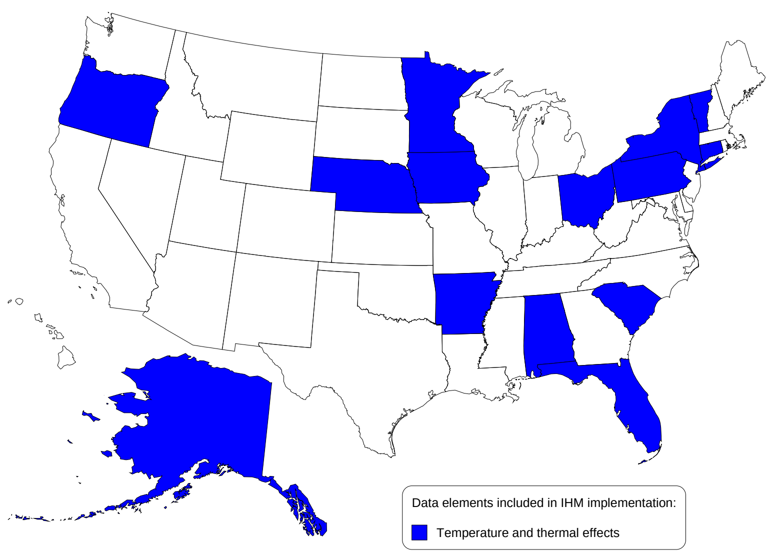


Figure 9.10: Maps of the states with DOTs measuring temperature and thermal effects.

With regard to data collection and transmission, 87% of State DOTs who implement/apply IHM systems use automated data acquisition and transmission systems with variety of procedures. Manual collection of acquired data is also used by 13% State DOTs, as shown in Figure 9.11.

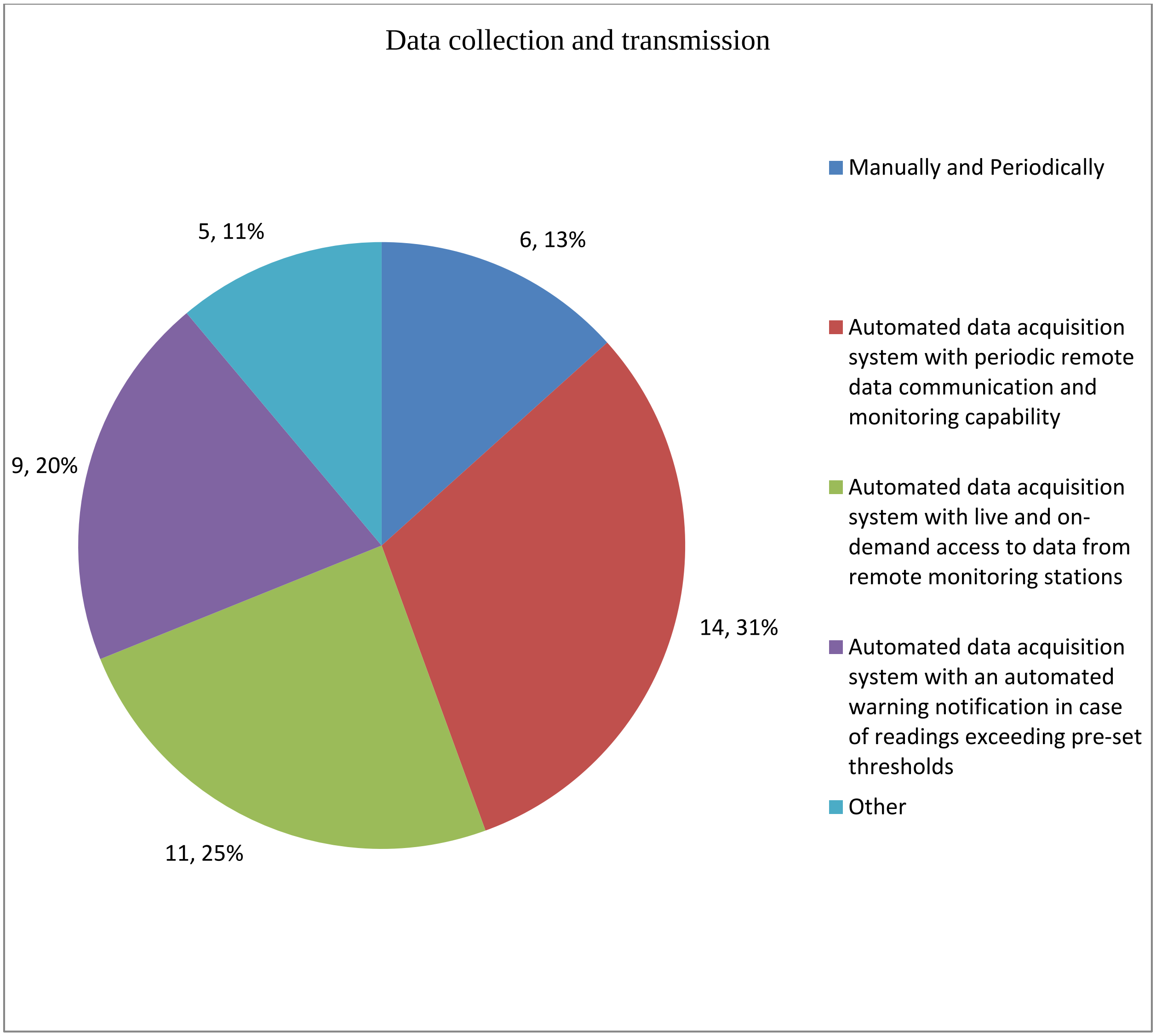


Figure 9.11: Data of State DOTs methods of data collection and transmission.

Ninety four percent of State DOTs who implemented IHM systems perform analysis on the collected data. Thirty eight percent of those hired contractors to perform data reduction and analysis, while 33% of State DOTs analyze the collected data in house. Figure 9.12 depicts the survey results on data analysis and synthesis.

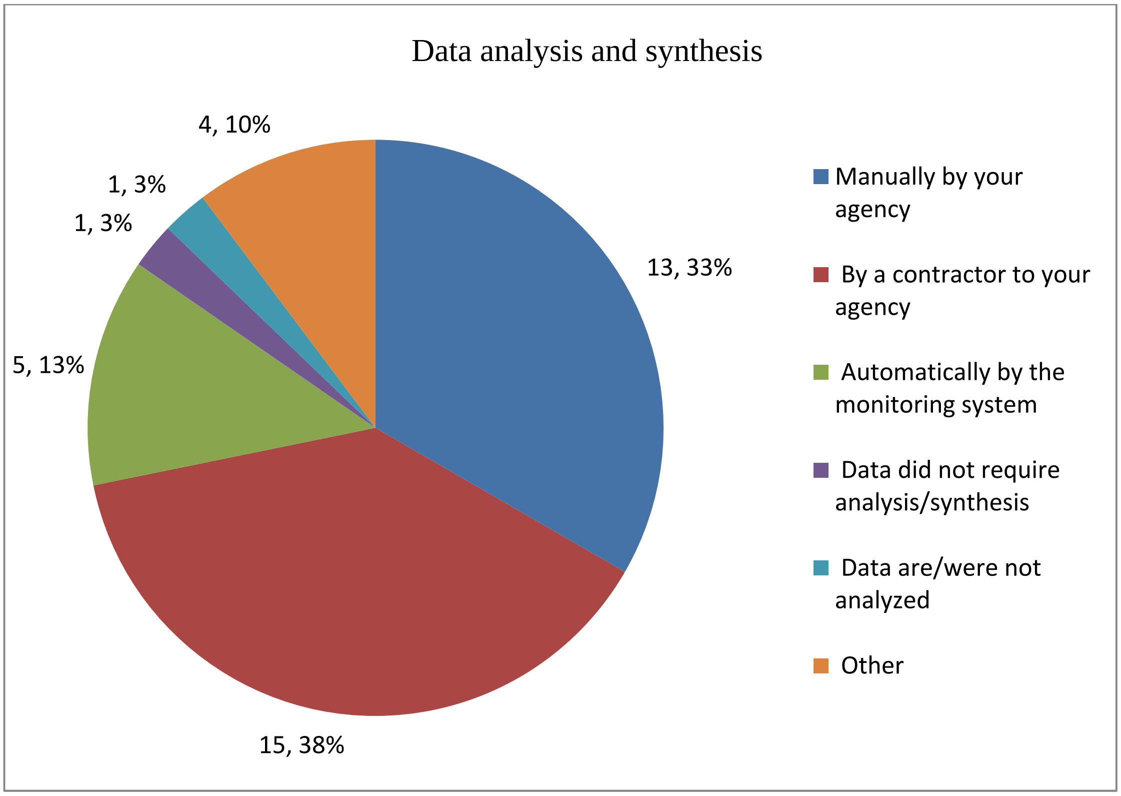


Figure 9.12: Analysis and synthesis of data collected through IHM.

The level, scale and extent of implementing IHM monitoring are of importance to this study. While 34% of State DOTs implemented IHM for research purposes, 30% and 25% of State DOTs used IHM applications for safety monitoring and for maintenance and planning purposes, respectively. Figure 9.13 presents the results of the survey with regard to the level/scale of implementing IHM systems by State DOTs.

Figure 9.14 and 9.15 depict maps of the states with highway agencies implementing IHM system applications for safety monitoring and for research purposes, respectively.

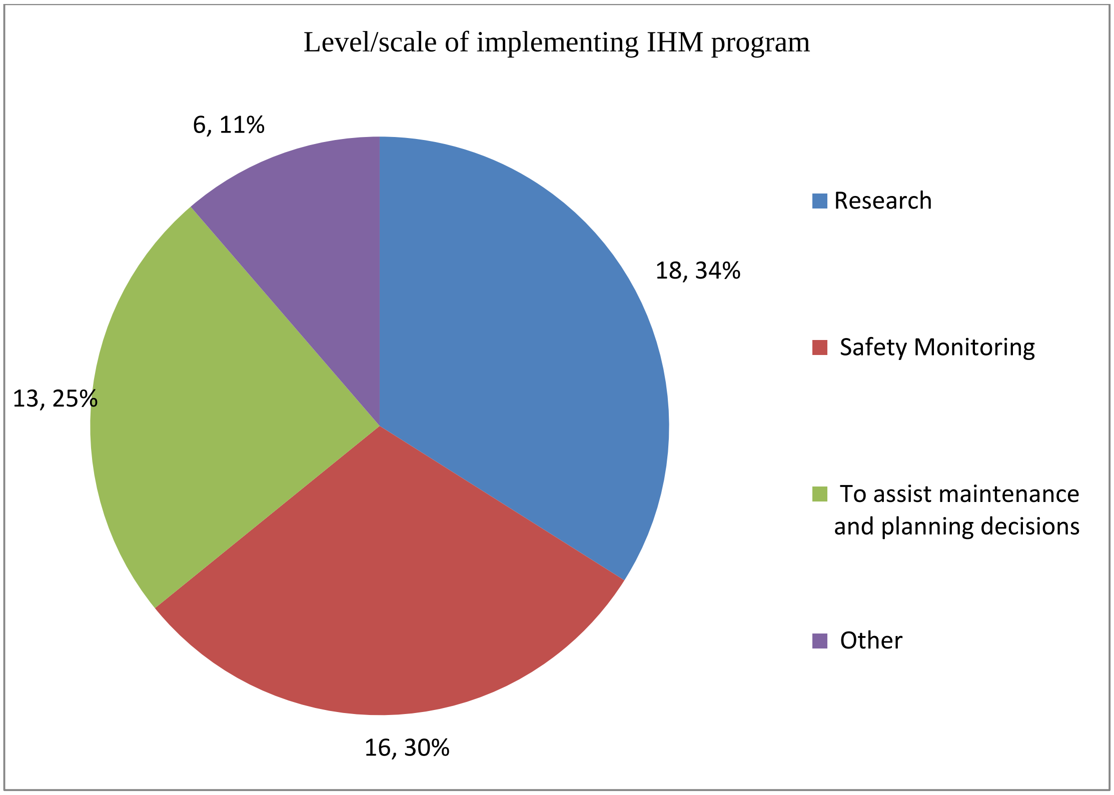


Figure 9.13: Level, scale, and extent of implementing IHM program by State DOTs.

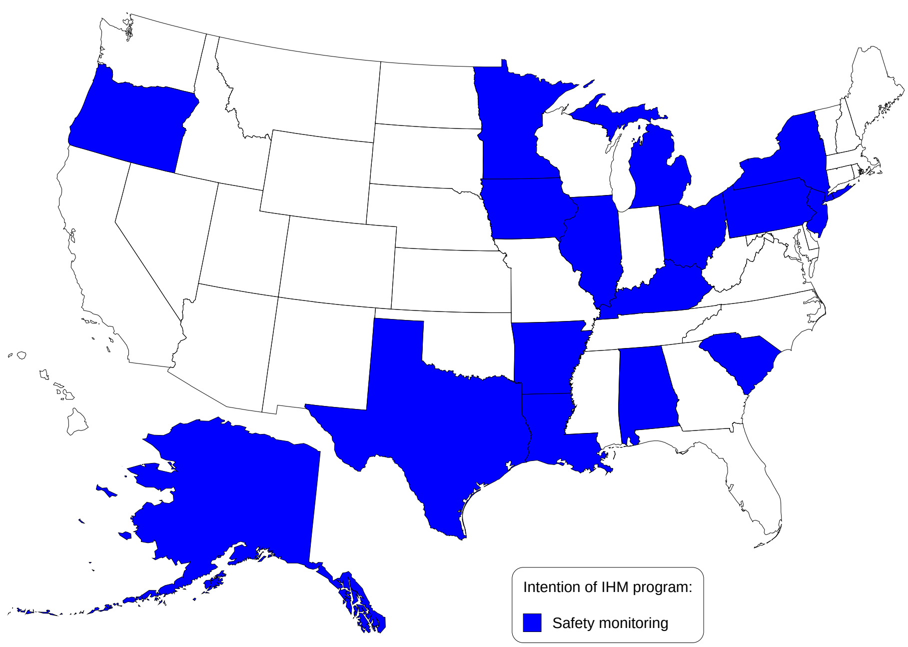


Figure 9.14: Maps of the states with highway agencies implementing IHM system applications for safety monitoring.

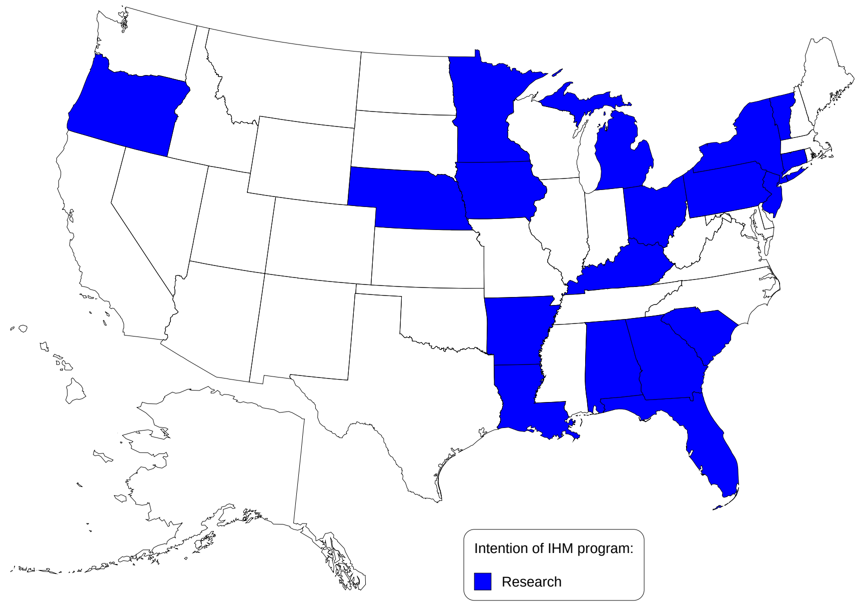


Figure 9.15: Maps of the states with highway agencies implementing IHM system applications for research purposes.

Literature review of challenges and issues associated with IHM indicated that cost of implementation as well as lack of analysis of the extensive amounts of collected data top the list of obstacles and challenges facing State DOTs in using IHM systems. These issues were confirmed by the survey results in which 47% of the State DOTs who implement IHM systems raised the cost as the major impediment to the wide-spread acceptance/use of IHM programs by State DOTs. In addition, 17% of the State DOTs who implement IHM systems stated that lack of analysis and use of collected data is one of the main obstacles they face. Figure 9.16 depicts the results of the survey questionnaire on the impediments facing the acceptance of implementing IHM systems.

State highway agencies with the answer “other” provided the following:

- Man-power
- Too much data
- Government procurement procedure
- Generally requires extra effort, project champion and coordinator to evaluate data and provide reporting

Figure 9.17 presents a map of the states with DOTs stating that cost is the main obstacle in a wide implementation of IHM systems.

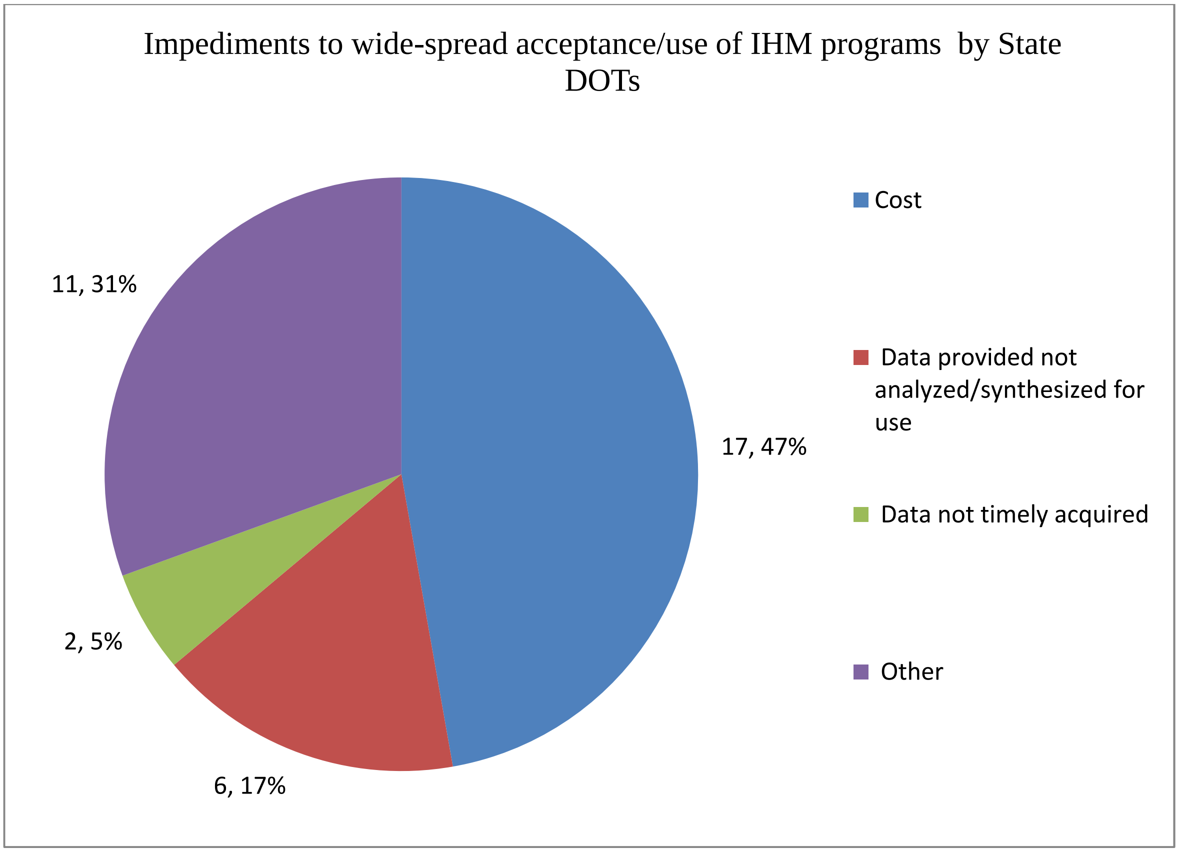


Figure 9.16: The most important impediments to wide-spread acceptance/use IHM program by State DOTs

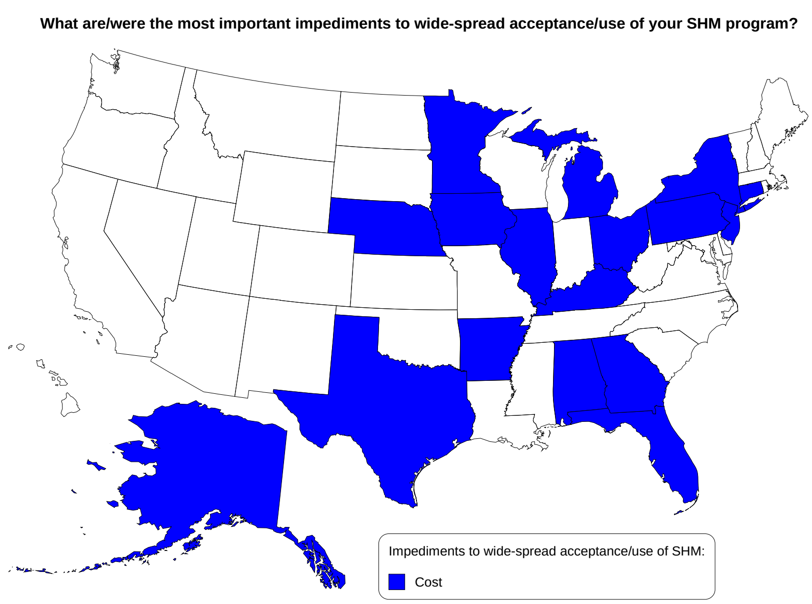


Figure 9.17: Map of the states with DOTs stating that cost is the main obstacle in a wide implementation of IHM systems.

Figure 9.18 depicts survey results of State DOTs response on the effectiveness of IHM systems implemented. The IHM systems used by State DOTs were considered effective according to the survey results with 87% of State DOTs answered “yes.” The remaining 13% gave answers under “other” including:

- Research too early to tell but the outcomes to date have obvious potential for future deployment
- We are making progress

Figure 9.19 shows states map with highway agencies that consider their implementation of IHM systems is effective.

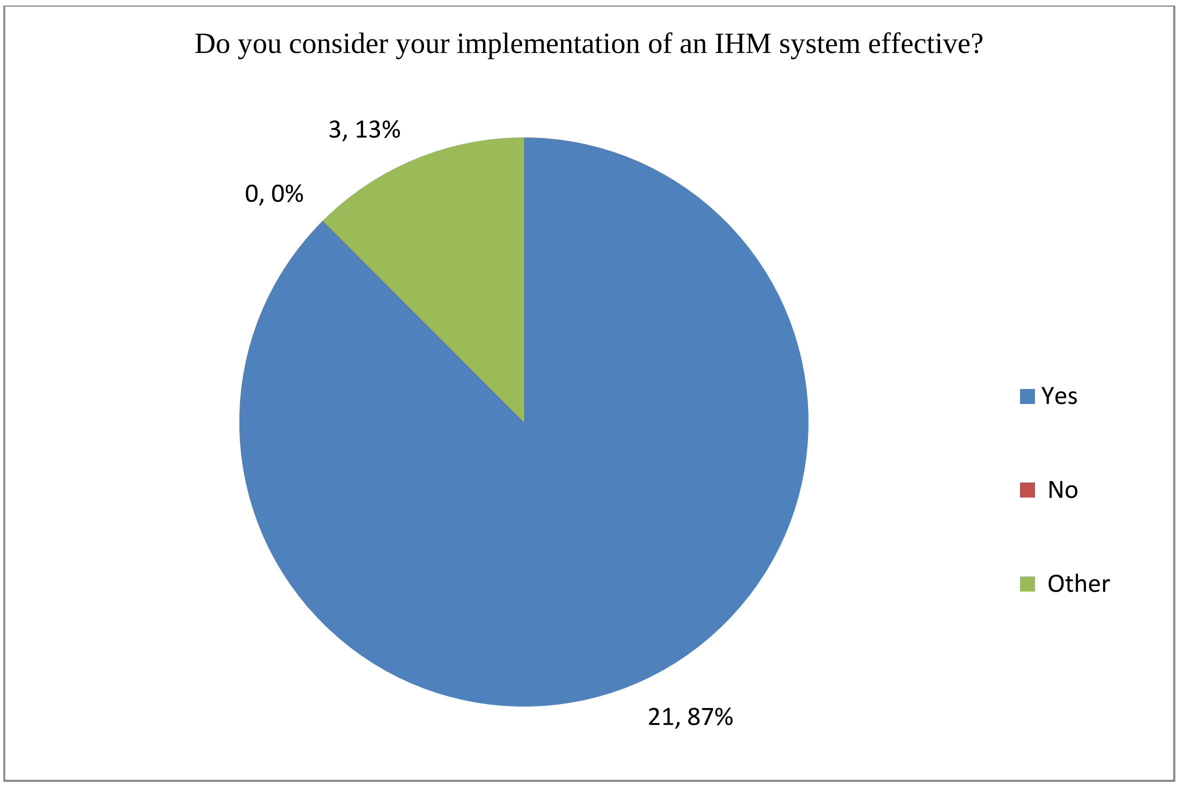


Figure 9.18: The analysis of survey results on State DOTs response on the effectiveness of IHM systems implemented.

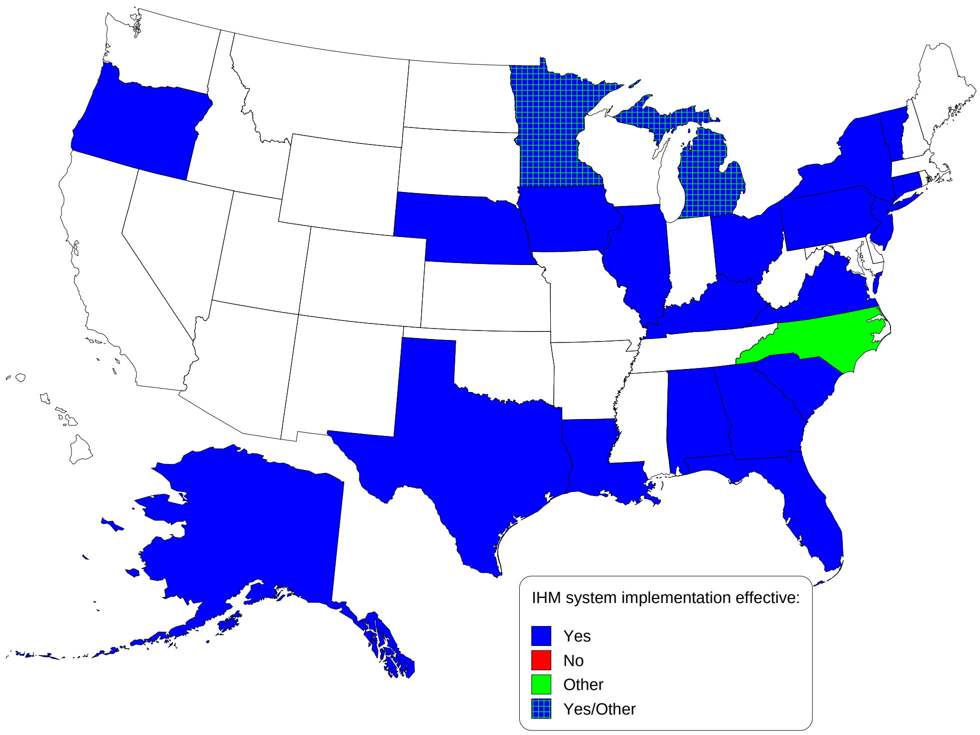


Figure 9.19: Map of states with highway agencies that consider their implementation of IHM systems is effective.

All state highway agencies who used/implemented IHM systems indicated that they will apply this technology again. Fifty two percent of State DOTs indicated that they will use the same system and settings used before while 48% stated that they will improve, modify and enhance their future systems, as presented in Figures 9.20 and 9.21.

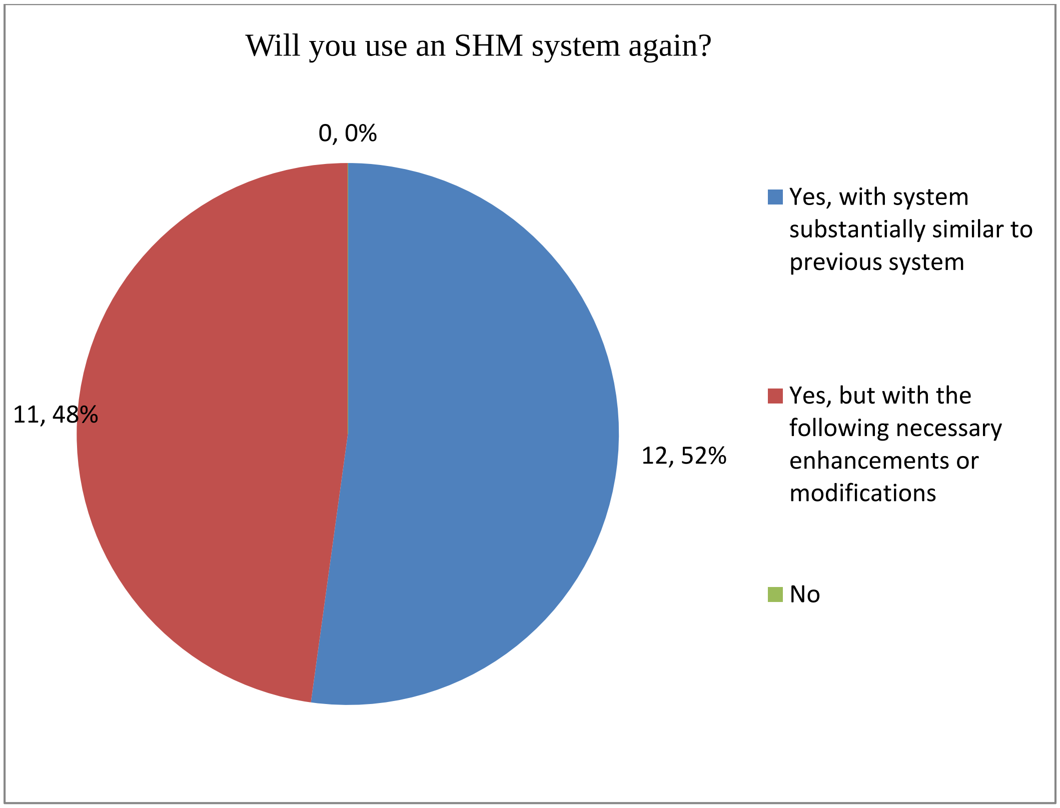


Figure 9.20: Response of State DOTs on using IHM systems for future applications.

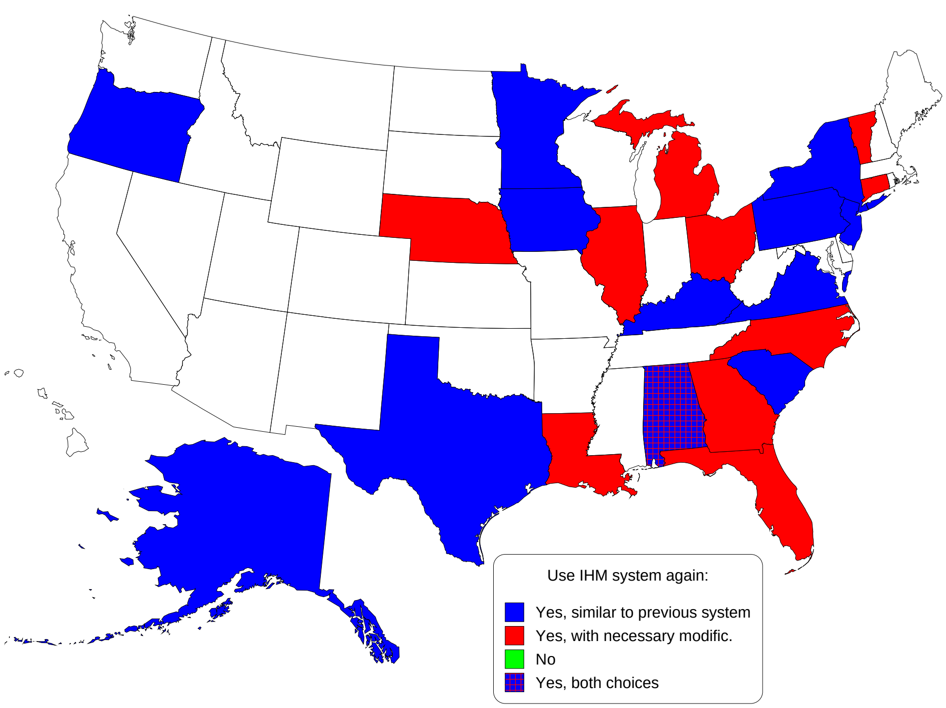


Figure 9.21: Map of states that will continue using IHM systems for future applications.

Chapter 10

Conclusions and Recommendations

This report represents the forward-planning necessary for the proper development, acquisition, installation and maintenance of a dynamic health monitoring network for transportation infrastructure systems.

Based on the comprehensive literature review conducted, information collected from companies with IHM technologies, case histories reported, comprehensive survey of state highway agencies in the U.S. and Canada, data collection and analysis, the following conclusions are reached:

1. IHM can be effectively applied to monitor various components of transportation infrastructure. The infrastructure components most commonly instrumented and investigated are bridges and pavements

2. The challenges/impediments of implementing IHM include the initial cost of such systems, operational costs, data collection/storage/analysis, and technologies for the use of collected data for real-time decision making.

3. The potential beneficial applications of IHM data was demonstrated by analyzing data from a recently completed WHRP study (0092-0601). As part of that study, wheel wander and WIM systems were imbedded in the pavement surface to document the applied wheel loadings. A sampling of data stored within the WHRP project 0092-06-01 database was extracted for this study to evaluate the distribution of wheel loads within the pavement lane (including effects of vehicle type and time of day), determine the spectra of applied loads (for mechanistic analysis of pavement performance), and develop a low-cost and accurate wheel load measurement system.

4. Data collected by IHM systems can be analyzed and used to evaluate the performance of infrastructure systems, as indicated by the use of the Marquette Interchange pavement instrumentation data. Archived data was analyzed by the research team and used to predict the pavement performance of the north leg of the Marquette Interchange.

5. The Zoo Interchange is identified as a viable project site for implementing an IHM testbed system in southeast Wisconsin. This interchange includes a variety of infrastructure components, including bridges, pavements, earth retaining structures, and slopes.

6. Cost estimates of the implementing health monitoring systems for transportation infrastructure that include sensors, data acquisition system, data transmission, data storage and processing depend on the circumstances surrounding each project. Based on the information collected, a rough estimate of the cost of IHM can range between $450 and $4,000 per sensor based on the number of sensors and other factors. As the number of sensors increases, the cost per sensor decreases for a given system parameters.

7. The survey shows that there is significant interest in implementation of IHM by State DOT's for research purposes as well as applications for other intents.

8. Planning for IHM should include data analysis and decision guides. Advance planning for interpreting the typically large and complex data sets that are collected is crucial in a successful IHM program.

Based on the research conducted, the following recommendations are proposed:

1. One or more of the currently planned construction projects in Wisconsin could be selected for infrastructure health monitoring (IHM).

2. An IHM implementation team should be developed for each selected IHM project. The team should include key personnel who can help develop specific project goals.

Chapter 10

Conclusions and Recommendations

This report represents the forward-planning necessary for the proper development, acquisition, installation and maintenance of a dynamic health monitoring network for transportation infrastructure systems.

Based on the comprehensive literature review conducted, information collected from companies with IHM technologies, case histories reported, comprehensive survey of state highway agencies in the U.S. and Canada, data collection and analysis, the following conclusions are reached:

1. IHM can be effectively applied to monitor various components of transportation infrastructure. The infrastructure components most commonly instrumented and investigated are bridges and pavements

2. The challenges/impediments of implementing IHM include the initial cost of such systems, operational costs, data collection/storage/analysis, and technologies for the use of collected data for real-time decision making.

3. The potential beneficial applications of IHM data was demonstrated by analyzing data from a recently completed WHRP study (0092-0601). As part of that study, wheel wander and WIM systems were imbedded in the pavement surface to document the applied wheel loadings. A sampling of data stored within the WHRP project 0092-06-01 database was extracted for this study to evaluate the distribution of wheel loads within the pavement lane (including effects of vehicle type and time of day), determine the spectra of applied loads (for mechanistic analysis of pavement performance), and develop a low-cost and accurate wheel load measurement system.

4. Data collected by IHM systems can be analyzed and used to evaluate the performance of infrastructure systems, as indicated by the use of the Marquette Interchange pavement instrumentation data. Archived data was analyzed by the research team and used to predict the pavement performance of the north leg of the Marquette Interchange.

5. The Zoo Interchange is identified as a viable project site for implementing an IHM testbed system in southeast Wisconsin. This interchange includes a variety of infrastructure components, including bridges, pavements, earth retaining structures, and slopes.

6. Cost estimates of the implementing health monitoring systems for transportation infrastructure that include sensors, data acquisition system, data transmission, data storage and processing depend on the circumstances surrounding each project. Based on the information collected, a rough estimate of the cost of IHM can range between $450 and $4,000 per sensor based on the number of sensors and other factors. As the number of sensors increases, the cost per sensor decreases for a given system parameters.

7. The survey shows that there is significant interest in implementation of IHM by State DOT's for research purposes as well as applications for other intents.

8. Planning for IHM should include data analysis and decision guides. Advance planning for interpreting the typically large and complex data sets that are collected is crucial in a successful IHM program.

Based on the research conducted, the following recommendations are proposed:

1. One or more of the currently planned construction projects in Wisconsin could be selected for infrastructure health monitoring (IHM).

2. An IHM implementation team should be developed for each selected IHM project. The team should include key personnel who can help develop specific project goals.

References

Osama Y. Abudayyeh, Joseph Barbera, Ikhlas Abdel-Qader, Hubo Cai, and Eyad Almaita. Towards Sensor-Based Health Monitoring Systems for Bridge Decks: A Full-Depth Precast Deck Panels Case Study, Hindawi Publishing Corporation, Advances in Civil Engineering, Volume 2010, Article ID 579631, 14 pages

Murad Abu-Farsakh “Structural Health Monitoring System at the I-10 Twin Span Bridge over Lake Pontchartrain.”

Azarbayejani M., El-Osery A.I., and Reda Taha, M.M. (2009), "Entropy-Based Optimal Sensor Networks for Structural Health Monitoring of a Cable-Stayed Bridge," Journal of Smart Structures and Systems, Vol. 5, No. 4, 2009, pp. 483-494.

Azarbayejani, M., A. I. El-Osery, et al. (2008). "A probabilistic approach for optimal sensor allocation in structural health monitoring." Smart Materials & Structures 17(5).

Barber, D.C.: A review of image reconstruction techniques for electrical impedance tomography. Med. Phys. 16, 162–169 (1989)

Beard S., Qing P., Hamilton M. and Zhang D. (2004). "Multifunctional software suite for structural health monitoring using SMART technology", Proc. 2nd Eur. Workshop on Structural Health Monitor.

Brent M. Phares, Terry J. Wipf, Lowell F. Greimann, and Yoon-Si Lee. Health Monitoring of Bridge Structures and Components Using Smart-Structure Technology, WHRP 05-03 Report Vol. 1.

Carkhuff, B. and Cain, R. 2003, Corrosion sensors for concrete bridges, IEEE Instrumentation and Measurement Magazine, 6(2), 19-24.

CHANG, F.-K. (2007). "Structural Health Monitoring 2007: Quantification, Validation, and Implementation." FA9550-07-1-0306: 28.

Chen, B., Wu, K.R. and Yao, W. 2004a. Piezoresistivity in Carbon Fiber Reinforced Cement Based Composites, Journal of Materials Science and Technology, 20(6):746-750.

Chen, B., Wu, K.R. and Yao, W. 2004b. Conductivity of Carbon Fiber Reinforced Cement-based Composites, Cement and Concrete Composite, 26:291-297.

Chen, P., Chung, D., 1996. A comparative study of concretes reinforced with carbon, polyethylene and steel fibers and their improvement by latex addition, *ACI Mater J* 93 (2), pp.129-133.

Chen, P., Chung, D., 1996. Carbon fiber reinforced concrete as an intrinsically smart concrete for damage assessment during static and dynamic loading, ACI Mater J 93 (4), pp. 341-350.

Chen, P., Chung, D., 1996. Low-drying-shrinkage concrete containing carbon fibers, Composites, Part B 27B (1996), pp.269-274.

Chong, K.P.: Nanotechnology in civil engineering. Adv. Struct. Eng. 8, 325–330(2005)

Chung, D., 2002. Piezoresistive Cement-Based Materials for Strain Sensing, J. Intelligent Material Systems and Structures 13(9), 599-609.

Decher, G.: Fuzzy nanoassemblies toward layered polymeric multicomposites. Science277, 1232–1237 (1997)

DeWolf, John T., P. F. D. A., Eric G. Feldblum, Robert G. Lauzon (2006). "BRIDGE MONITORING NETWORK-INSTALLATION AND OPERATION." 45.

Dharap, P., Li, Z., Nagarajaiah, S., Barrera, E.V.: Nanotube film based on single-wallcarbon nanotubes for strain sensing. Nanotechnology 15, 379–382 (2004)

Djordjevic, B. B. (1990). NDE in space. *Proc. Ultrasonics Symposium, IEEE* , 997-1002.

Elias, V., Christopher, B. R., and Berg, R. R. (2001). “Mechanically stabilized earth walls and reinforced soil slope design and construction guidelines.” FHWA-NHI-00-045, 394 pgs.

Farrar, C. R. and Worden, K. (2007), An introduction to structural health monitoring, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 365(1851), pp. 303-315.

Fraden, 2004. Handbook of Modern Sensors: Physics, Designs, and Applications, 3rd edition. Springer USA 589 p.

Fraser, M. _2006_. “Development and implementation of an integrated framework for structural health monitoring.” Ph.D. dissertation, Dept. of Structural Engineering, Univ. of California at San Diego, La Jolla, Calif.

Michael Fraser; Ahmed Elgamal; Xianfei He; and Joel P. Conte Sensor Network for Structural Health Monitoring of a Highway Bridge JOURNAL OF COMPUTING IN CIVIL ENGINEERING © ASCE / JANUARY/FEBRUARY 2010 p.11-24

Fu, X., Chung, D., 1996. Self-Monitoring of Fatigue Damage in Carbon Fiber Reinforced Cement, Cem. Concr. Res. 26(1), 15-20

Gao, Y. and Spencer Jr., B. F. (2008)., “Structural Health Monitoring Strategies for Smart Sensor Networks,” Newmark Structural Engineering Laboratory Report Series, No. 011, University of Illinois at Urbana-Champaign.

Gastineau, Andrew, Johnson, Tyler, Schultz, Arturo (2009), Bridge Health Monitoring and Inspection-A Survey of Methods. MNDOT Report No. MN/RC 2009-29. St. Paul, MN. 194.

Giacomo Moriconi, Tarun R. Naik, 2010, Monitoring System to Provide Assurance for Maintenance of Structures, Practice Periodical on Structural Design and Construction, Vol. 15, No. 1, pp. 4-8

Gomez, J., Zubia, J., Aranguren, G., Arrue, J., Poisel, H., and Saez, I. (2009). "Comparing polymer optical fiber, fiber Bragg grating and traditional strain gauge for aircraft structrural health monitoring." *Applied Optics*, Vol. 48, No. 8, pp. 1436-1443.

Graf, L., 2007, Effect of Relative Humidity on Expansion and Microstructure of Heat-Cured Mortars, RD139, Portland Cement Association, Skokie, Illinois.

Haggenmueller, R., Gommans, H.H., Rinzler, A.G., Fischer, J.E., Winey, K.I.:Aligned single-wall carbon nanotubes in composites by melt processing methods.Chem. Phys. Lett. 330, 219–225 (2000)

Hornyak N. J.; Crovetti J. A.; Newman D. E.; and Schabelski J. P., Prepetual Pavement Instrumentation for the Marquette Interchange Project- Phase 1, Transportation Research Centre-Marquette University, August 2007, SPR#0092-06-01

Hou, T.C., Loh, K.J., Lynch, J.P.: Spatial conductivity mapping of carbon nanotubecomposite thin films by electrical impedance tomography for sensing applications. Nanotechnology 18, 315-501 (2007)

Hughs, E. A.; Liang, Z.; Idriss, R. L. and Newtson, C. M.,2005, "In-Situ Modulus of Elasticity for a High Performance Concrete Bridge," ACI Materials Journal, V. 102, No. 6, pp. 458-458.

Idriss, R. L.; White, K. R.; Pate, J. W.; Vohra, S. T.; Chang, C. C.; Danver, B. A. and Davis, M. A., 1998, "Monitoring and Evaluation of an Interstate Highway Bridge Using a Network of Optical Fiber Sensors," Fiber Optic Sensors for Construction Materials and Bridges, Ansari, F., ed., Technomic Publishing, Lancaster, PA, pp. 148-158.

I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci. A survey on sensor networks. *IEEE Communications Magazine*, 40(8):102.114, August 2002.

Kang, I., Heung, Y.Y., Kim, J.H., Lee, J.W., Gollapudi, R., Subramaniam, S., Narasimhadevara, S., Hurd, D., Kirikera, G.R., Shanov, V., Schulz, M.J., Shi, D., Boerio,J., Mall, S., Ruggles-

Wren, M.: Introduction to carbon nanotubes and nanofiber smartmaterials. Compos. Part B-Eng. 37, 382–394 (2006)

Kang, I., Schulz, M.J., Kim, J.H., Shanov, V., Shi, D.: A carbon nanotube strain sensor for structural health monitoring. Smart Mater Struct. 15, 737–748 (2006)

Kim, S., S. Pakzad, et al. (2006). "Health Monitoring of Civil Infrastructures Using Wireless Sensor Networks." 19.

Klahorst, J. T.; Klingner, R. E. and Kreger, M. E., 2005, Mitigation Techniques for In-Service Structures with Premature Concrete Deterioration: Development and Verification of New Test Method, Center for Transportation Research, The University of Texas at Austin, Austin, TX.

Koerner R. M. ; Koerner G. R., Recommended Layout of Instrumentation to Monitor Potential Movement of MSE Walls, Berms and Slopes, April 2011, GRI White Paper #19

Li H, Xiao HG, Ou JP. 2004. A study on mechanical and pressure-sensitive properties of cement mortar with nanophase materials. Cement Concrete Res, 34: 435-8.

Li, H.; Xiao, H.G.; Ou, J.P. 2006, Effect of compressive strain on resistance of carbon black-filled cement-based composites. Cement and Concrete Composites, Cem. Concr. Compos, 28:824-828.

Li, H.; Xiao, H.G.; Ou, J.P. 2008, Electrical property of cement-based composites filled with carbon black under long-term wet and loading condition, Composites Science and Technology, 68:2114-2119

Lin, Mark W., Thaduri, Jagan. and Gopu, Vijaya. (2003). A Distributed Strain Sensor for Bridge Monitoring. UTCA Report Number 02304. University Transportation Center for Alabama, Tuscaloosa, Alabama.

Liu, S. C. (2008). "Sensors, smart structures technology and steel structures." Smart Structures and Systems 4(5): 517-530.

Livingston R, Slade J, Player J, Kristoff S, Kokkins S, Lusignea R. (2006) Fiber optic sensing of internal relative humidity for improved concrete performance. In: Sobolev K. editor. Proceedings of the first international conference on advanced construction materials, Monterrey, México;. p. 125–138.

Loh, K. J., Lynch, J. P. and Kotov, N. (2006), Nanoengineered inductively coupled carbon nanotubes wireless strain sensors, Proceedings of the 4th World Conference on Structural Control and Monitoring, (4WCSCM), San Diego, CA.

Loh, K.J., Kim, J.H., Lynch, J.P., Kam, N.W.S., Kotov, N.A. (2007): Multifunctional layerby-layer carbon nanotube-polyelectrolyte thin films for strain and corrosion sensing.Smart Mater. Struct. 16, 429–438

Loh, K.J. (2008): Development of multifunctional carbon nanotube nanocomposite sensors for structural health monitoring. Ph.D. Thesis, University of Michigan, Ann Arbor, MI

Lopez-Higuera, J. M. ed., 2002, Handbook of Optical Fibre Sensing Technology John Wiley & Sons, New York.

Lynch, J. P. and Hou, T.-C. 2005, Conductivity-based strain and damage monitoring of cementitious structural components, SPIE 12th Annual International Symposium on Smart Structures and Materials, San Diego, CA, March 6-10.

Lynch, J.P., K.J. Loh, T.-C.Hou, and N. Kotov, 2009, 1Nanocomposite Sensing Skins for Distributed Structural Sensing, NICOM3 - Third International Symposium on Nanotechnology in Construction, Prague, pp. 303-308.

M. M. Reda Taha, M. A. (2009). "Monitoring Long-Term In-Situ Behavior of Installed Fiber Reinforced Polymer- Report I: State of the Art in Structural Health Monitoring of Bridges and FRP Systems." report NM08TT-02: 115.

Mamedov, A.A., Kotov, N.A., Prato, M., Guldi, D., Wicksted, J., Hirsch, A.: Molecular design of strong SWNT/polyelectrolyte multilayers composites. Nat. Mat. 1, 190–194 (2002)

Mason, Robert B. Jr., et al. (2009), “A Novel Integrated Monitoring System for Structural Health Management of Military Infrastructure”, DoD Corrosion Conference.

Mehta, P. K. and Monteiro, P., 2006, Concrete: Microstructure, Properties and Materials, McGraw-Hill, New York.

Michie, W. C.; Culshaw, B.; Konstanaki, M.; McKenzie, I.; Kelly, S.; Graham, N. B. and Moran, C., 1995, "Distributed pH and Water Detection Using Fiber-Optic Sensors and Hydrogels," Journal of Lightwave Technology, V. 13, No. 7, pp. 1415-1420.

Nalwa, H.S.: Nanostructured Materials and Nanotechnology. Academic Press, SanDiego (2002)

Nanni F, Auricchio F, Sarchi F, Forte G, Gusmano G. 2009, Self-sensing CF-GFRP rods as mechanical reinforcement and sensors of concrete beams. Smart Mater. 13: 1615-9

Nevers D. (2010), The development of electromagnetic sensors for structural health monitoring, MS thesis, University of Wisconsin, Milwaukee.

Nevers D., Zhao J., Sobolev K., and Hanson G., (2011) Investigation of Stress-Sensing Materials Based on EM Surface Wave Propagation for Steel Bridge Health Monitoring. *Construction and Building Materials* Vol. 25, pp. 3024–3029.

Phares, Brent M., Wipf, T.J., Greimann, Lowell F., and Lee, Y.S. (2005). "Health Monitoring of Bridge Structures and Components Using Smart-Structure Technology Volume I." WHRP report 0092-04-14.

Phares, Brent M., Wipf, T.J., Greimann, Lowell F., and Lee, Y.S. (2005). "Health Monitoring of Bridge Structures and Components Using Smart-Structure Technology Volume II." REPORT 0092-04-14: 215.

Pickard, W. F., Knoblauch, M., Peters, W. S. and Shen, A. 2006, Prospective energy densities in the forisome, a new smart material, Materials Science and Engineering, 26(1), 104-112.

Regaswamy Srinivasan, Robert Osiander, Jane W. Spicer,Francis B.Weiskopf, Jr., Kenneth R. Grossman, Russell P. Cain, Bliss G. Carkhuff, Laurel."WIRELESS MULTI-FUNCTIONAL SENSOR PLATFORM, SYSTEM CONTAINING SAME AND METHOD FOR ITS USE" US Patent No.: US 6,796,187 B2: Sep.28,2004

Rice, J. A. and Spencer Jr., B. F. (2009), "Flexible Smart Sensor Framework for Autonomous Full-scale Structural Health Monitoring," NSEL Report No. 18, University of Illinois at Urbana-Champaign.

Richard A. Livingston, 2002, Fiber Optic Sensor Networks for Monitoring Existing Bridges, in Rehabilitating and Repairing the Buildings and Bridges of the Americas, Wendichansky, D. and Pumarada-O'Neill, L. F., Editors., ASCE: Mayaguez, Puerto Rico. p. 65-75.

Richard A. Livingston, Jeremiah Slade, John Player, Susan B. Kristoff, Stephen J. Kokkins and Richard Lusignea, 2006, Fiber Optic Sensing of Internal Relative Humidity for Improved Concrete Performance; in: K. Sobolev (Ed.) First International Conference on Advanced Construction Materials, Monterrey, México, pp. 125-138.

Rodriguez Carmona, K., Lugo Cuevas, J.M., Marquez Lucero, A. (2006). Development of Fiber Optic Sensor For Monitoring of Crack Formation in Concrete Structures. In: Sobolev K. editor. Proceedings of the first international conference on advanced construction materials, Monterrey, México; 2006. p. 119-132.

Rytter, A. (1993). "Vibrational based inspection of civil engineering structures." PhD thesis, Department of Building Technology and Structural Engineering, Aalborg University, Denmark.

Schwartz G, Cerveny S, Marzocca AJ. 2000. A numerical simulation of the electrical resistivity of carbon black filled rubber. Polymer, 41: 6589–95.

Shaffer, M.S.P., Windle, A.H. (1999): Fabrication and characterization of carbon nanotube/poly(vinyl alcohol) composites. Adv. Mat. 11, 937–941

Shi, Z., Chung, D., 1999. Carbon fiber reinforced concrete for traffic monitoring and weighing in motion, CemConcr Res 29 (3), pp. 435-439.

Silvia Santini, Daniel Rauch Minos: A Generic Tool for Sensor Data Acquisition and Storage

Smart Structures and Materials 2003: Smart Systems and Nondestructive Evaluation for Civil Infrastructures. Edited by Liu, Shih-Chi. Proceedings of the SPIE, Volume 5057, pp. 20-28 (2003).

Sohn, H., C. R. Farrar, et al. (2004). A Review of Structural Health Monitoring Literature form 1996-2001, LA-13976-MS. Los Alamos National Laboratory. http://www.lanl.gov/projects/ei/shm/publications.shtml

Song, G., Gu, H., Mo, Y. L., Hsu, T. T. C., Dhonde, H. and Zhu, R. H. (2004), Health monitoring of a reinforced concrete bridge bent-cap using piezoceramic materials, Proceedings of the Third European Conference on Structural Control (3ECSC) (Vienna, Austria), July.

Song, G., Gu, H., Mo, Y. L., Hsu, T. T. C., Dhonde, H. and Zhu, R. H. (2005), Health monitoring of a concrete structure using piezoceramic materials, Proceedings of 2005 SPIE International Symposium on Smart Structures and Materials, 5765, 5765-5713.

Song, G., Olmi, C. and Gu, H. 2005, An over height collision detection and evaluation system for bridge girder using piezoelectric transducer, Proceedings of 2nd International Conference on Structural Health Monitoring of Intelligent Infrastructure (Shenzhen, China).

Structural health monitoring / edited by Daniel Balageas, Claus-Peter Fritzen and Alfredo Güemes. London : ISTE, 2006. 495 p.

Todd, M.; Johnson, G.; Vohra, S. T.; Chen-Chang, C.; Danver, B. A. and Malsawma, L., 1999, "Civil Infrastructure Monitoring with Fiber Bragg Grating Sensors," Structural Health Monitoring, Chang, F. K., ed., Technomic Publishing Co., Lancaster PA, pp. 351- 370.

Vaisala, 2006, Users Guide: Vaisala HUMICAP Set for Measuring Humidity in Concrete HM44, Vaisala, Helsinki, Finland.

Washer, G.A., Rosenblad, B. Morris, S.E. (2009). Remote Health Monitoring for Asset Management. Report No. OR09-019. 56.

Watts, P.C.P., Hsu, W.K., Chen, G.Z., Fray, D.J., Kroto, H.W., Walton, D.R.M. (2001): Alow resistance boron-doped carbon nanotube-polystyrene composite. J. Mater.Chem. 11, 2482–2488

Wen, S., Chung, D., 2000. Damage Monitoring of Cement Paste by Electrical Resistance Measurement, Cem. Concr. Res. 30(12), 1979-1982.

Wen, S., Chung, D., 2005. Strain Sensing Characteristics of Carbon Fiber Reinforced Cement, ACI Mater. J. 102(4), 244-248.

Weston, D. F. (2006). Existing and future plans for the structural health monitoring of the Indian River Inlet Bridge. United States -- Delaware, University of Delaware. M.C.E.**:** 248.

Yu, X, Han, B., Kwon, E., 2009. A self-sensing carbon nanotube/cement composite for traffic monitoring, Nanotechnology, 20, pp. 1-5.

Zhang, Su., (2001). Sensor Data Management in Bridge Health Monitoring Systems. Ph.D. Thesis. Southern Illinois University, Carbondale, IL.

Zheng, L.X., Li, Z.Q. and Song, X.H. (2004a). Corrosion Monitoring of Rebar by Compression Sensitivity of CFRC, Journal of Experimental Mechnics, 19(2):206-210.

Zheng, L.X., Song, X.H. and Li, Z.Q. (2004b). Self-monitoring of the Deformation in Smart Concrete Strusrures, J. Huazhong Univ. of Sci. and Tech., 32(4):30-31.

Zoughi, R., and Kharkovsky, S. (2008). Microwave and Millimetre wave sensors for crack detection. *Fatigue & Fracture of Engineering Materials & Structures*, 695-713.

Diekfuss, J., Foley, C.M., Wan, B. (2011). *Fatigue Risks in the Connections of Sign Support Structures*, Progress Report, Phases 2 and 3, Wisconsin Highway Research Program, Wisconsin Department of Transportation, June 17, Madison, WI (to be presented).

Foley, C.M., Wan, B., Schneeman, C., Barnes, K., Komp, J., Liu, J., Smith, A. (2010). *In-Situ Monitoring and Testing of IBRC Bridges in Wisconsin*, Report WHRP 10-09, Wisconsin Highway Research Program, WisDOT SPR No. 0092-05-02, Wisconsin Department of Transportation, Madison, WI.

French, C., Hedegaard, B., Shield, C., Stolarski, H., Jilk, B. (2010). “I-35W St. Anthony Falls Bridge Structural Monitoring”, Annual Transportation Conference, Minnesota Department of Transportation, St. Paul, MN.

Wan, B., Foley, C.M, Komp, J. (2010). *Concrete Cracking in New Bridge Decks and Overlays*, Report WHRP 10-05, Wisconsin Highway Research Program, WisDOT SPR No. 0092-09-06, Wisconsin Department of Transportation, Madison, WI.

Watters, David G.; Jayaweera, Palitha; Bahr, Alfred J.; Huestis, David L.; Priyantha, Namal; Meline, Robert; Reis, Robert; Parks, Douglas

Wong, J-M., Goethals, J., and Stojadinovic, B., 2005, “Wireless Sensor Seismic Response Monitoring System Implemented on Top of NEESgrid,” in Health Monitoring and Smart Non-destructive Evaluation of Structural and Biological Systems IV, San Diego, CA, March 6–10, *Proceedings of the SPIE*, Vol. 5768, 74–84.

Appendices

Appendix A

SURVEY

Feasibility Study for a Freeway Corridor Infrastructure Health Monitoring Instrumentation Testbed

Project Objectives: The objective of this research is to evaluate the feasibility of initiating a health monitoring network for highway infrastructure.

Project Abstract: With current and near-term construction activities within the freeway system of Southeast Wisconsin, there is a unique opportunity to develop a detailed understanding of their in-service performance by implementing a health monitoring network that can serve as a living laboratory for the State of Wisconsin. Data from this health monitoring network can be used to develop and guide maintenance and inspection operations for these and other critical infrastructure components across the State. This monitoring network can also become a model for the nation, illustrating the benefits and cost savings from an integrated, proactive maintenance program.

Information of the person answering the survey:

Name:

Agency:

Position:

Contact information:

Survey Questions:

1. Are there any structural health monitoring (SHM) applications for transportation infrastructure that have been implemented or are currently being implementation in your agency of which you or someone you know are knowledgeable about?
   - Yes ➔ continue to questions 2 to 10 (questions 11 to 15 are optional)
   - No ➔ Stop, Thank you

2. Categories of transportation infrastructure for which SHM systems are implemented (circle all applicable):
   a. Bridges
   b. Pavements
   c. Tunnels
   d. Retaining structures
   e. Slopes (including soil erosion and scour)
   f. Structure for traffic control devices (signs, signals, etc)
   g. Roadside and median barriers
   h. Other: ____

3. What are/were the primary objectives behind your SHM implementation (circle all applicable)?
    a. Reduce manual data collection (minimize traffic disruption)
    b. Support infrastructure maintenance planning
    c. Identify critical/dangerous structural or safety conditions
    d. Other: -____

4. Which data elements were included in your SHM implementation? (circle all applicable items)
    a. Strain, deflection
    b. Tilt (rotation or lateral displacement)
    c. Support settlement
    d. Load/ pressure
    e. Vibrations
    f. Temperature and thermal effects
    g. Noise / sound
    h. Moisture/ice detection
    i. Chloride ion penetration / reinforcing bar corrosion
    j. Air quality
    k. pH/carbonation
    l. Other: ____

5. How were data collected and transmitted (circle all applicable)?
    a. Manually and periodically
    b. Automated data acquisition system with periodic remote data communication and monitoring capability
    c. Automated data acquisition system with live and on-demand access to data from remote monitoring stations
    d. Automated data acquisition system with an automated warning notification in case of readings exceeding pre-set thresholds.
    e. Other: ____

6. How were the data analyzed and synthesized (circle all applicable)?
    a. Manually by your agency
    b. By a contractor to your agency
    c. Automatically by the monitoring system
    d. Data did not require analysis/synthesis
    e. Data are/were not analyzed
    f. Other: ____

7. What was the intent of the SHM program (circle all applicable)?
    a. Research

b. Safety monitoring
c. To assist maintenance and planning decisions
d. Other: ____

8. What are/were the most important impediments to wide-spread acceptance/use of your SHM program? (circle all that apply)
   a. Cost
   b. Data provided not analyzed / synthesized for use
   c. Data not timely
   d. Other: -____

9. Do you consider your implementation of an SHM system effective?
   a. Yes
   b. No (please explain what in your view would make it effective)
   c. Other: ____

10. Will you use an SHM system again?
    a. Yes, with system substantially similar to previous system
    b. Yes, but with the following necessary enhancements or modifications:

    c. No (please explain why)

11. Provide detailed information on SHM implementation:
    a. Name and contact information of project manager / Principal Investigator

b. Publications/Reports (author, year, title, report number, publisher are sufficient)

12. If no publically available publications or reports exist, please provide information about technology types used:
    a. Sensors:
    b. data collection/monitoring systems:
    c. data synthesis systems:
    d. Other: ____
13. Provide rough estimates about the installed cost:
    a. Sensors (per unit and total, if possible): ____________________________________
    b. data collection/monitoring systems: _______________________________________
    c. data analysis/synthesis systems: ____
    d. Other: ____

14. State any problems/issues associated with:
    a. Sensors: ____
    b. data collection/monitoring systems: ____
    c. data synthesis systems: ____
    d. Other: ____

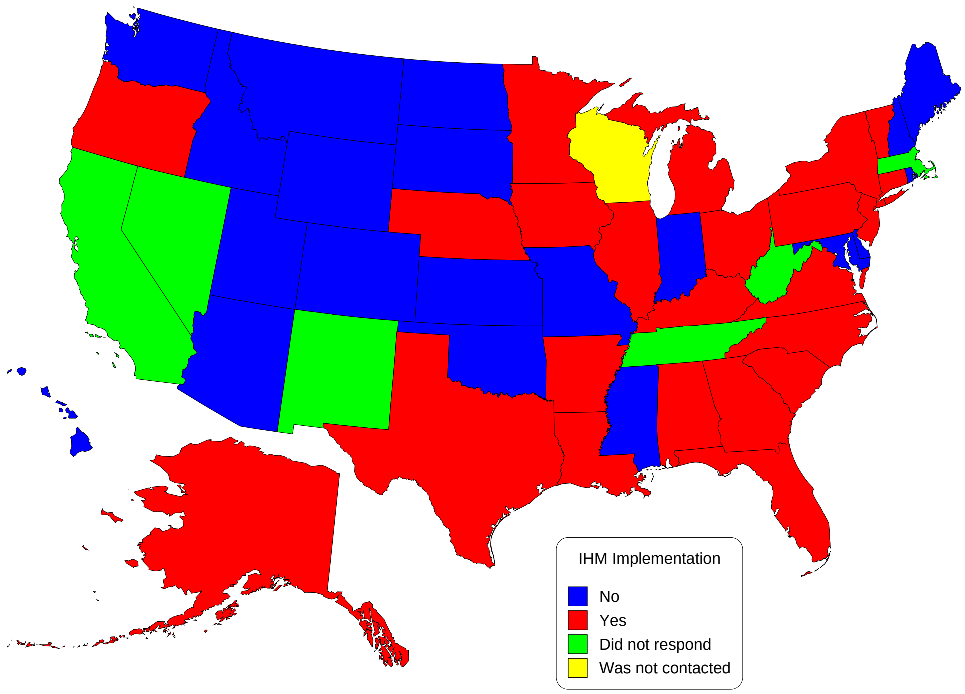
15. Comments/Recommendations: state any comment or recommendation based on your experience that help us in our research:

16. This question aims to gage your perceptions regarding the cost of SHM systems. For a hypothetical 50-sensor system, what is your expectation as to the total delivered cost?
    a. $500
    b. $5,000
    c. $50,000
    d. $500,000
    e. Other: ___________
    f. Do not know

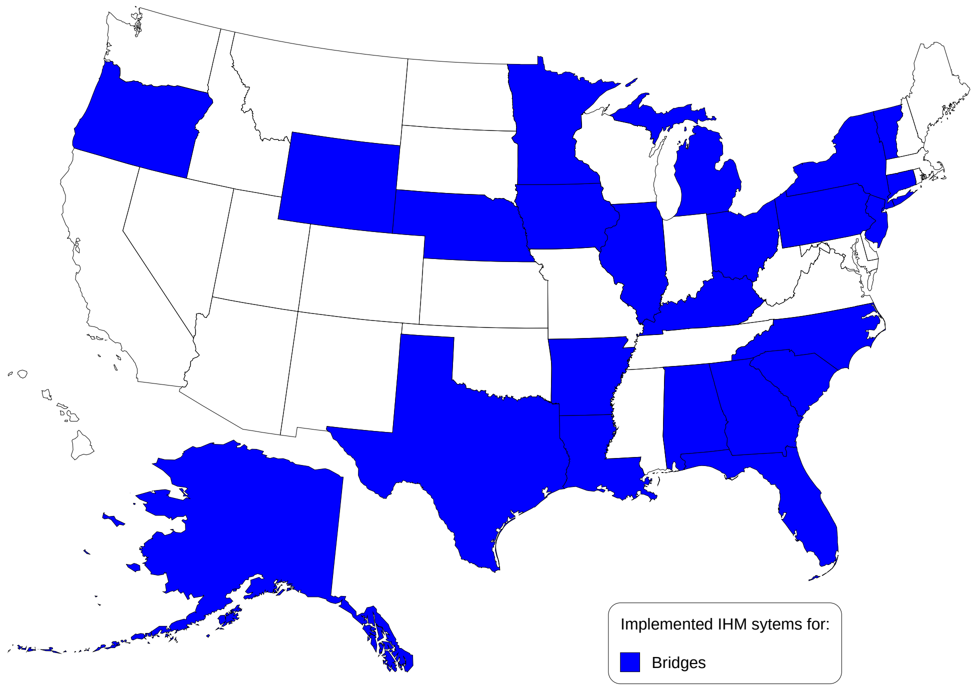
Appendix B

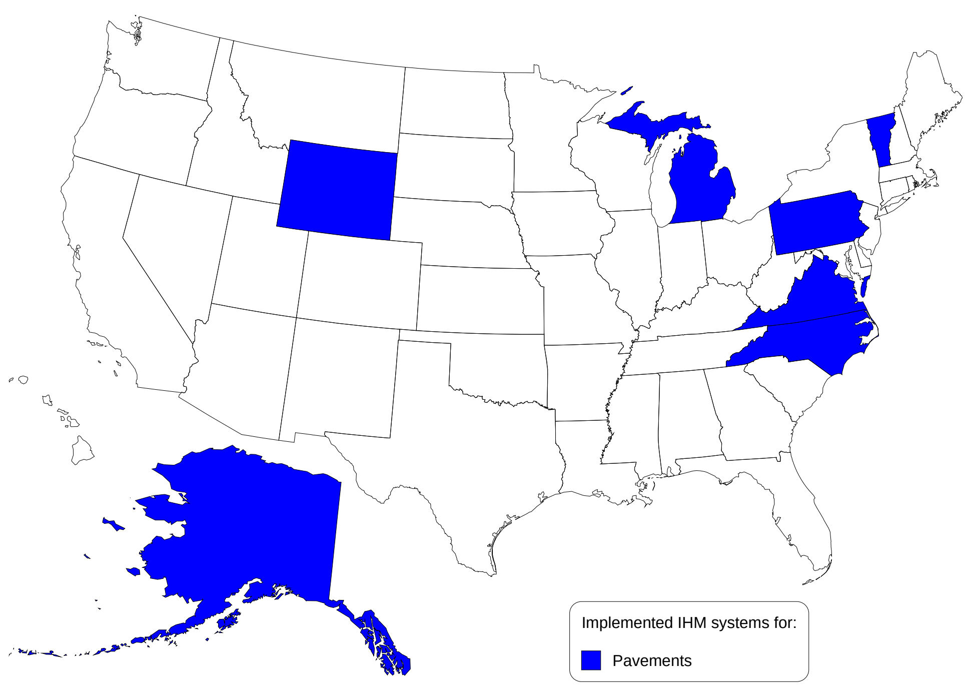
State DOTs survey maps

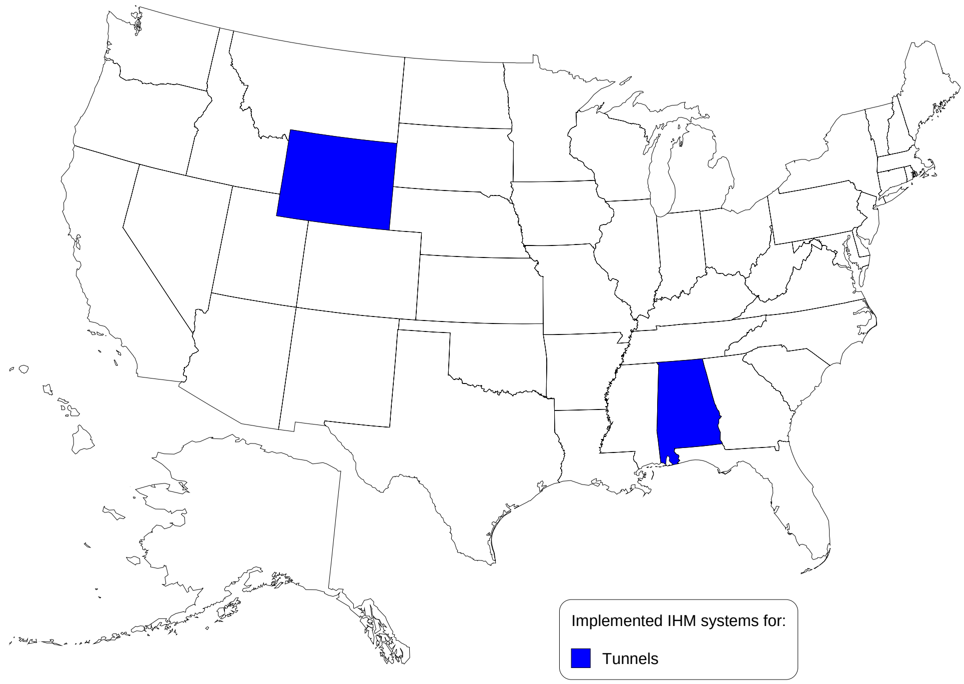
1. **Are there any Infrastructure Health Monitoring (IHM) applications for transportation infrastructure that have been implemented or are currently being implemented in your agency of which your or someone you know are knowledgeable about?**



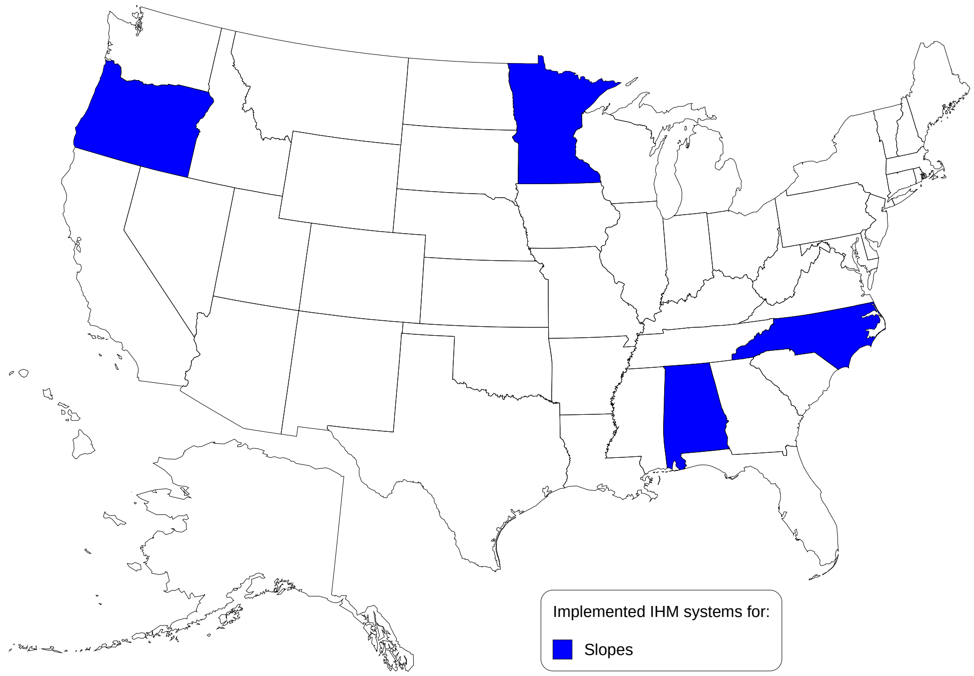
2. Categories of transportation infrastructure for which IHM systems are implemented.

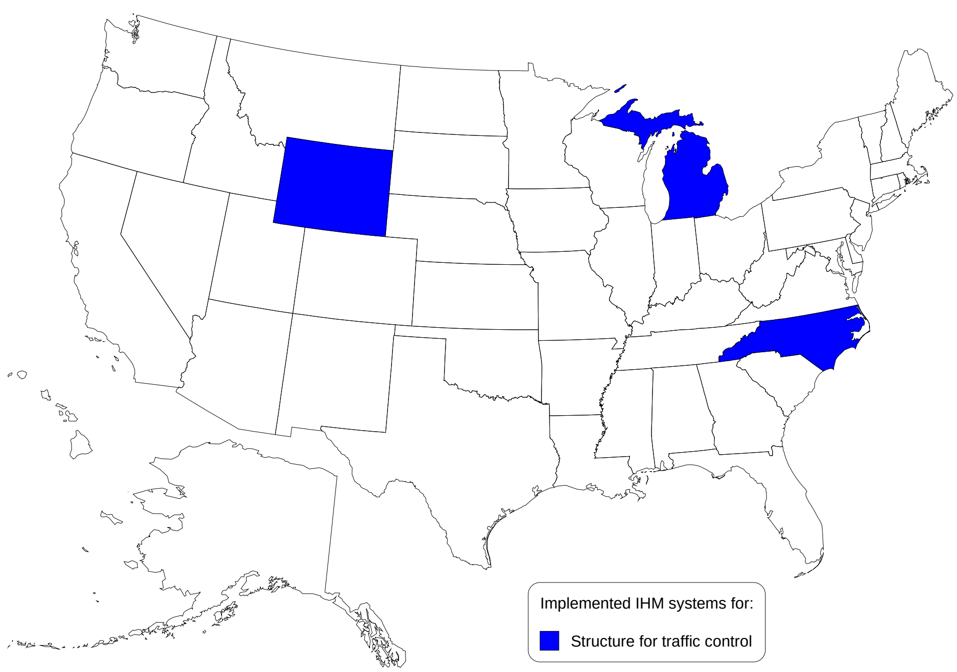




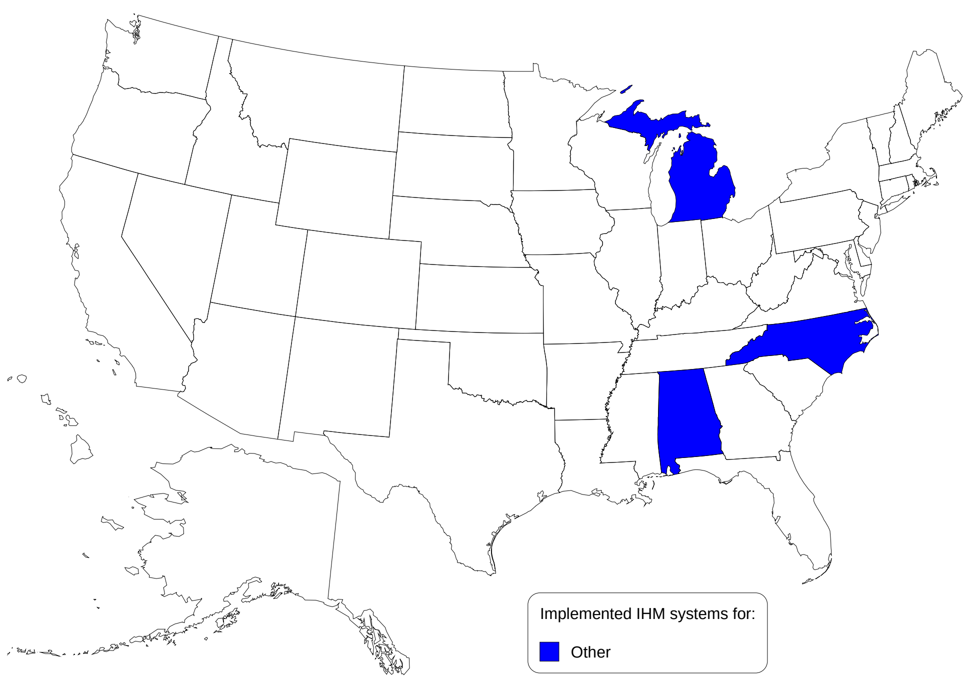

Implemented IHM systems for:
Tunnels


Implemented IHM system for:
Retaining structures

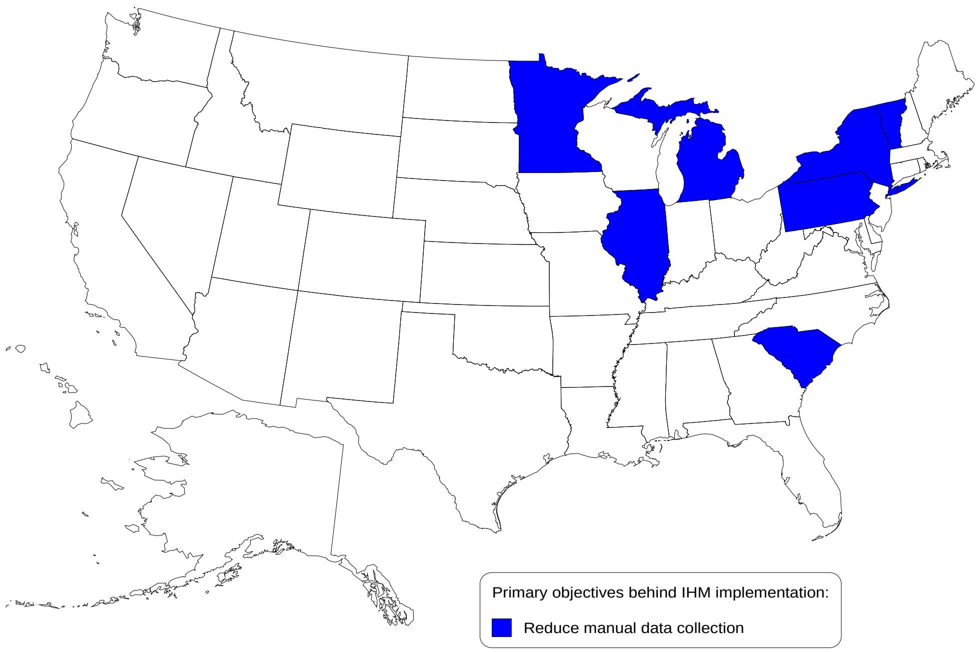

Implemented IHM systems for:
Slopes

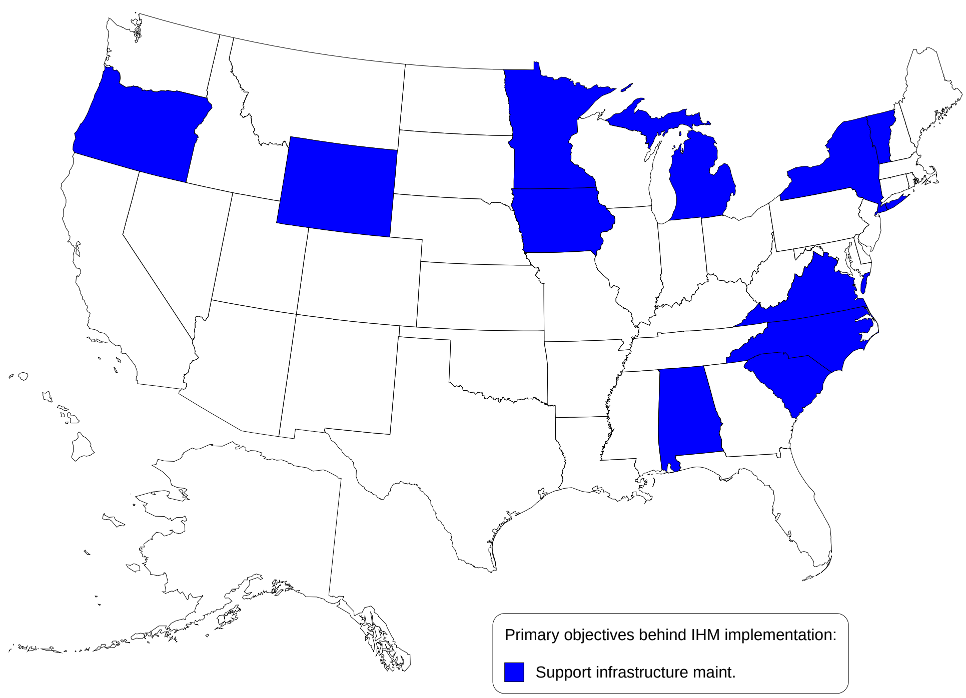

Implemented IHM systems for:
Structure for traffic control

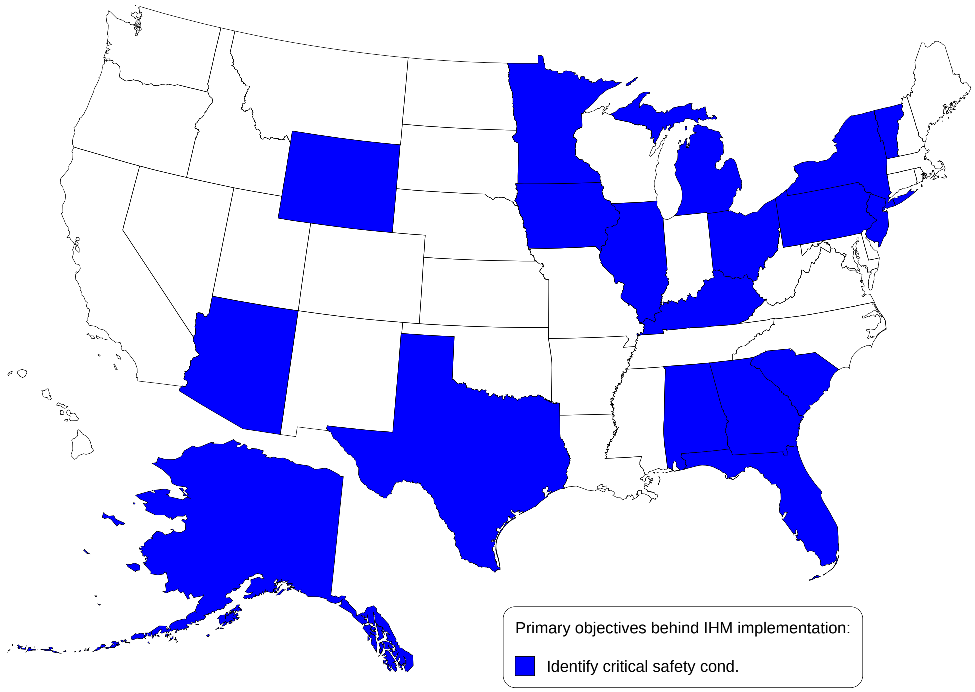

Implemented IHM systems for:
Roadside and median barriers

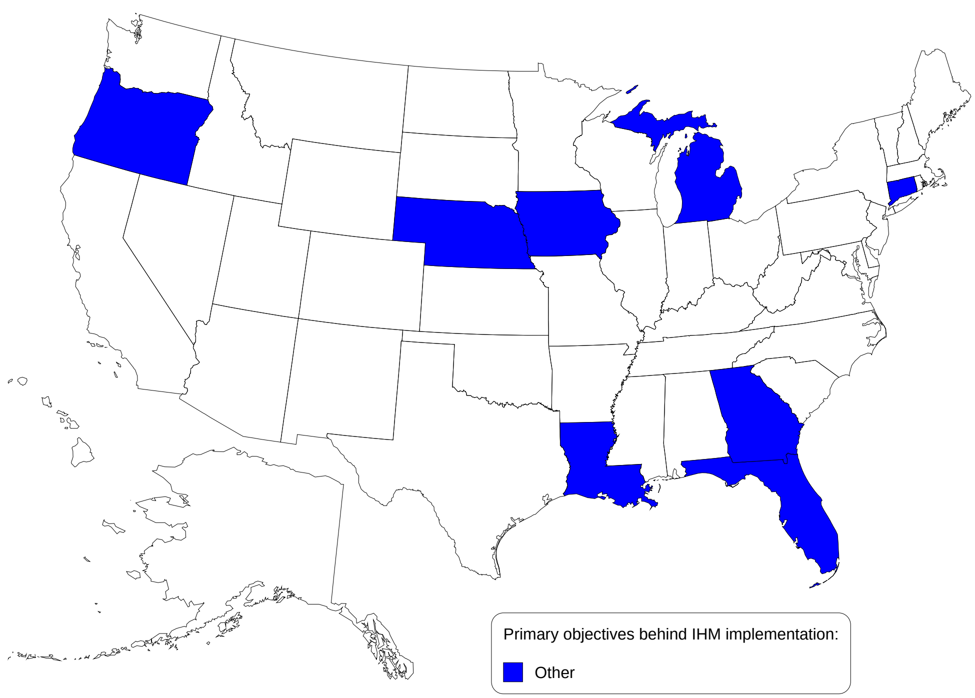

Implemented IHM systems for:
Other

3. What are/were the primary objectives behind your IHM implementation?

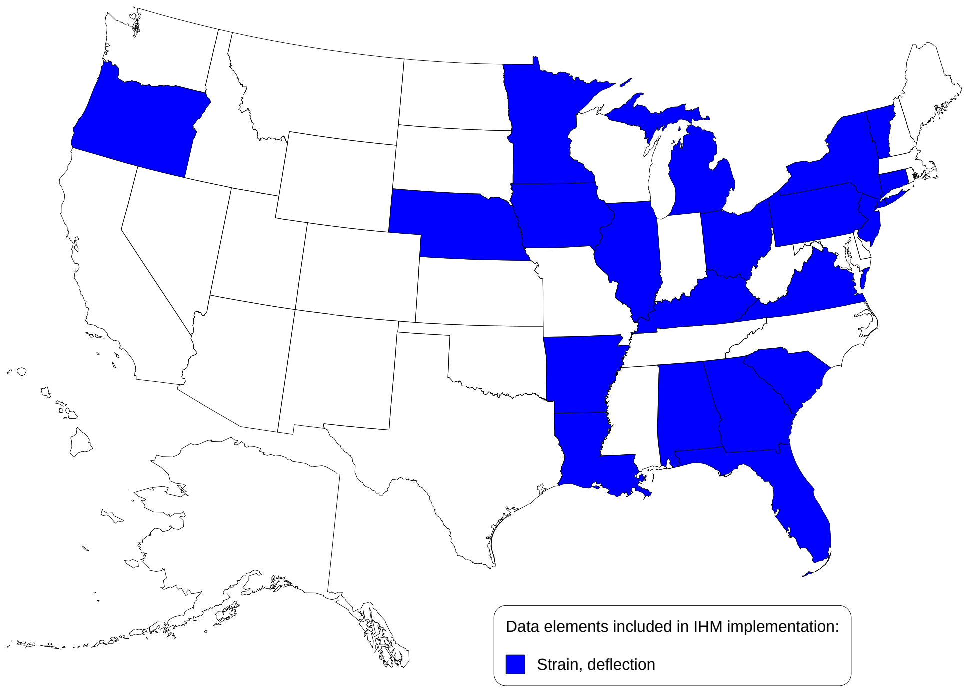


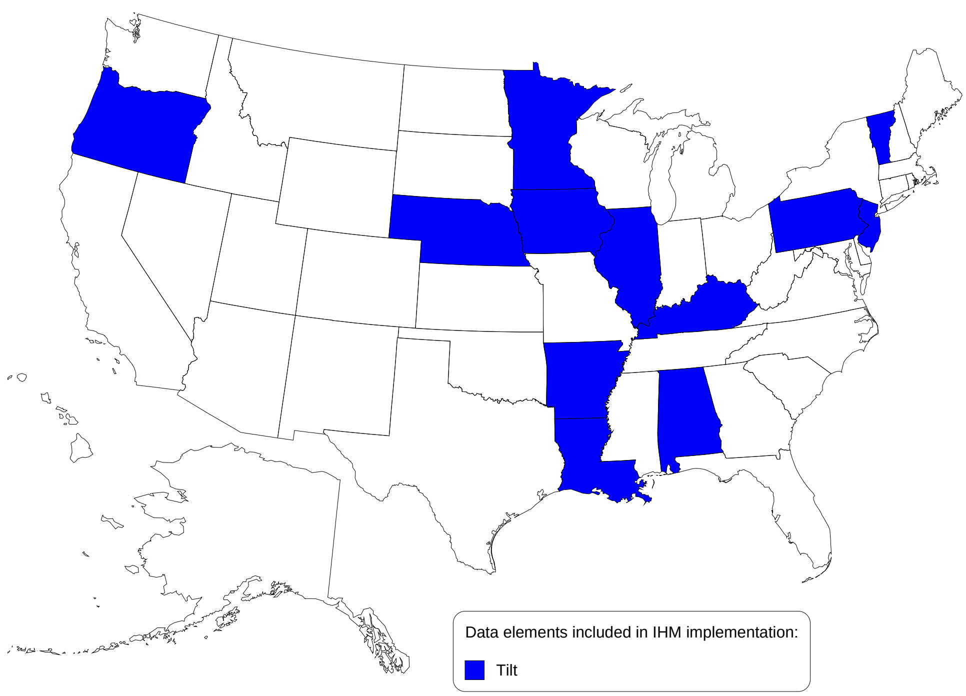


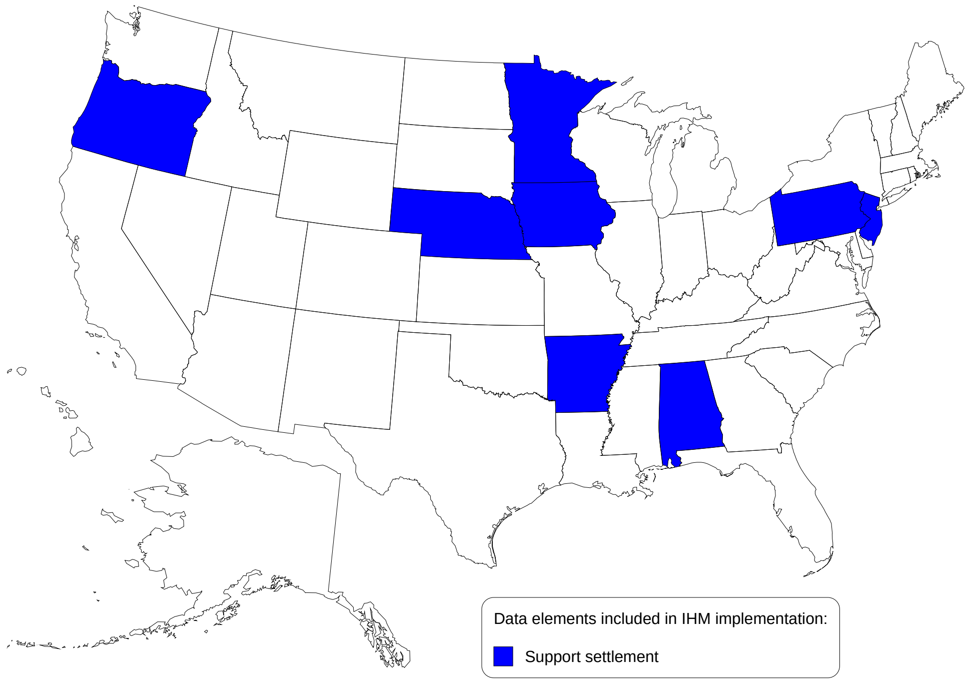

Primary objectives behind IHM implementation:
Identify critical safety cond.

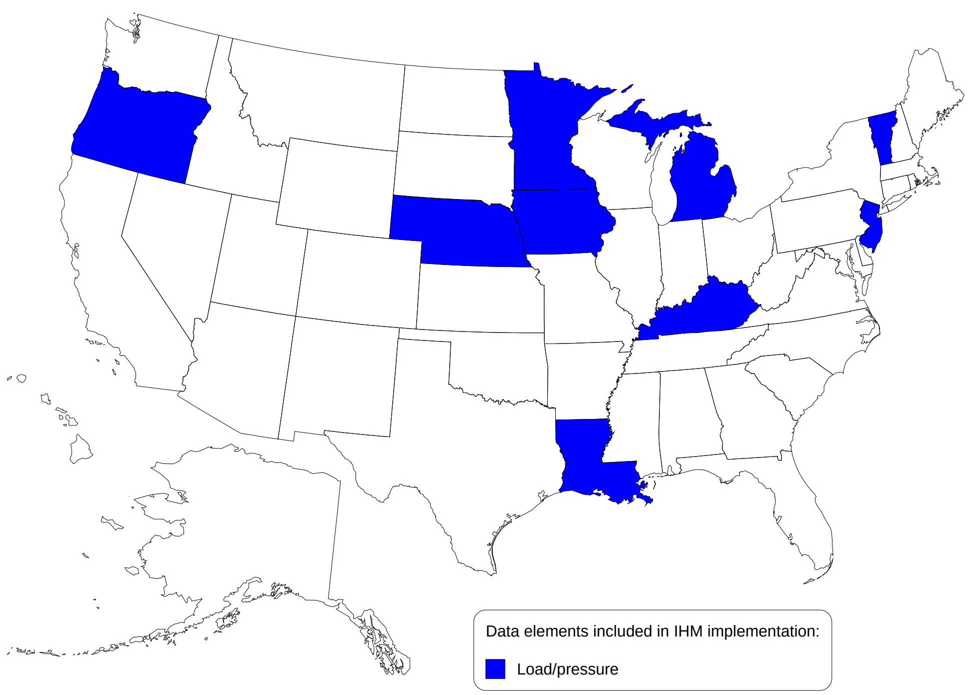

Primary objectives behind IHM implementation:
Other

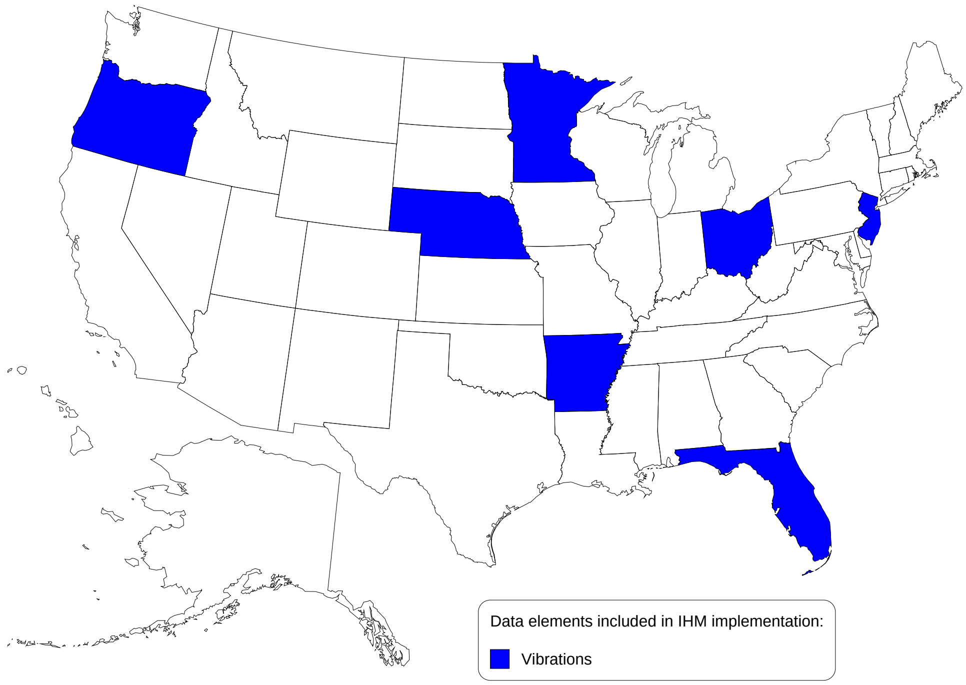
4. Which data elements are objectives behind your IHM implementation?

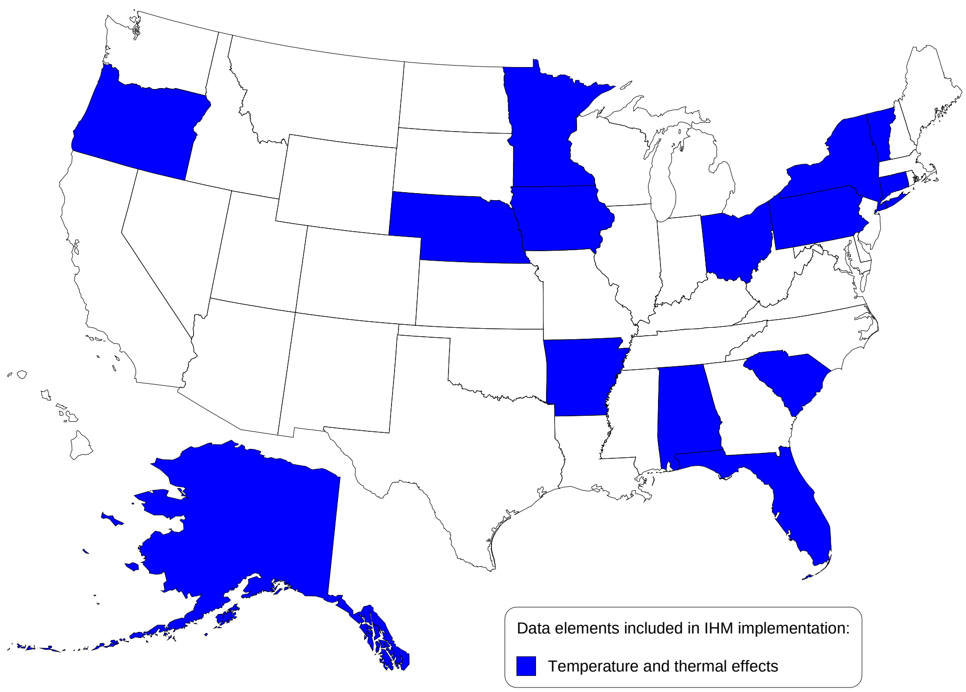


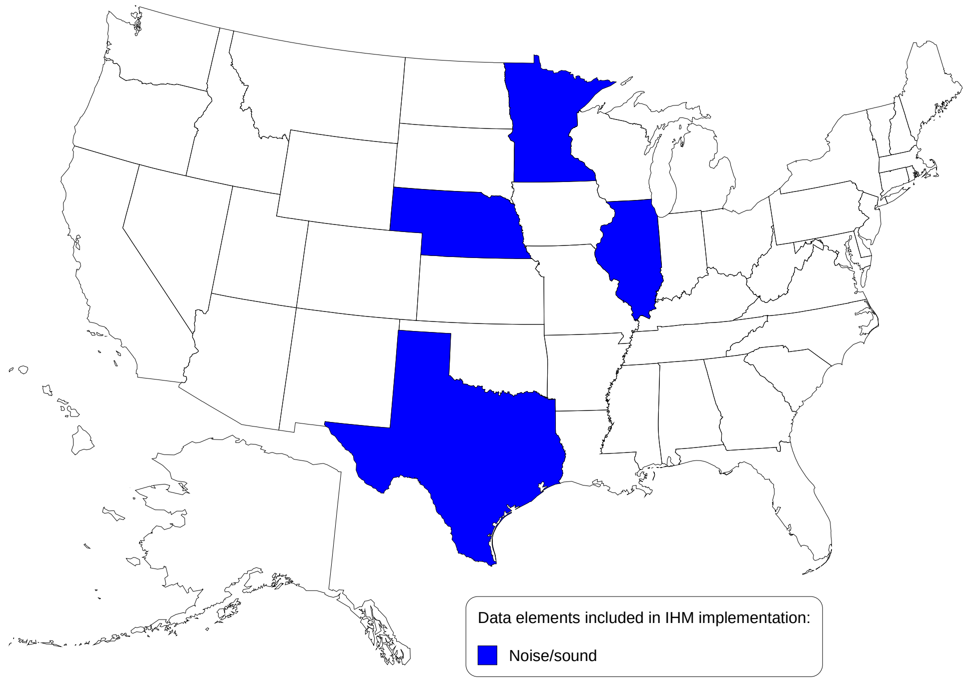


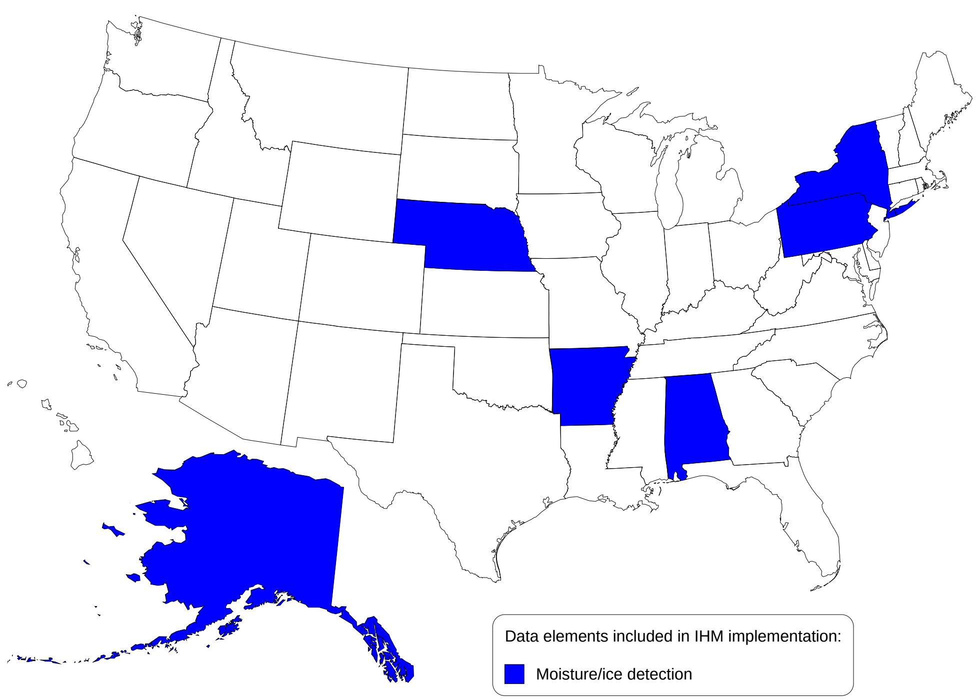

Data elements included in IHM implementation:
Support settlement

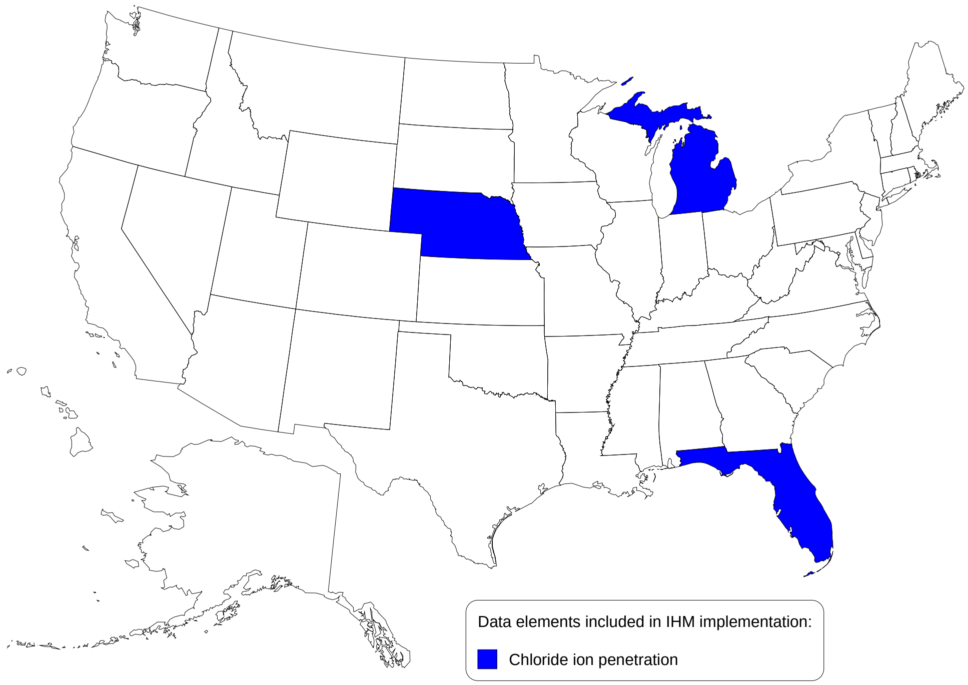

Data elements included in IHM implementation:
Load/pressure

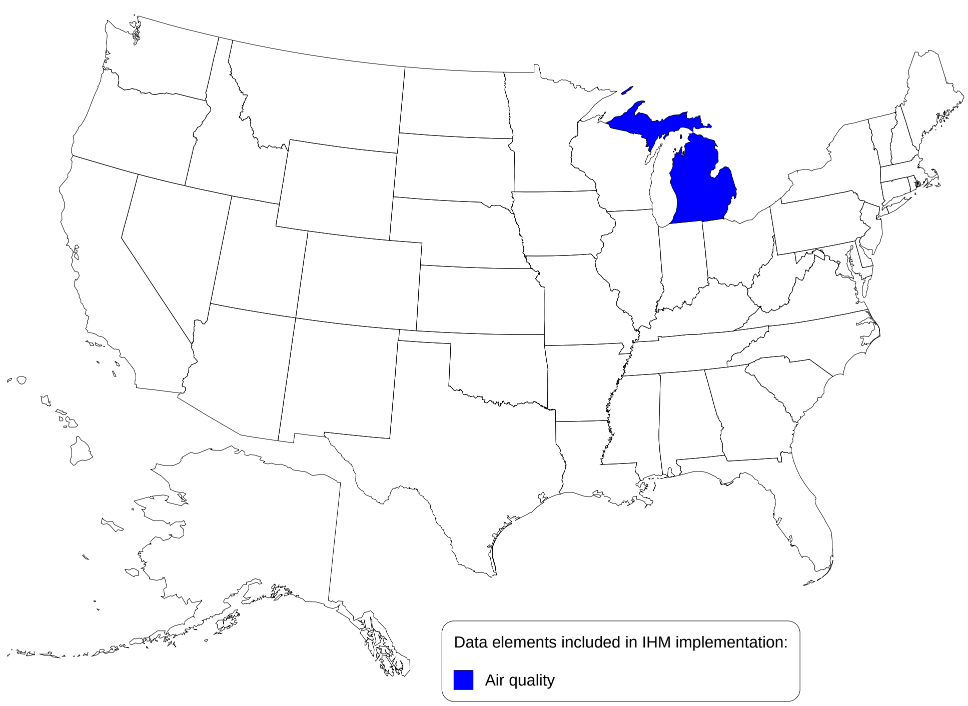

Data elements included in IHM implementation:
Vibrations

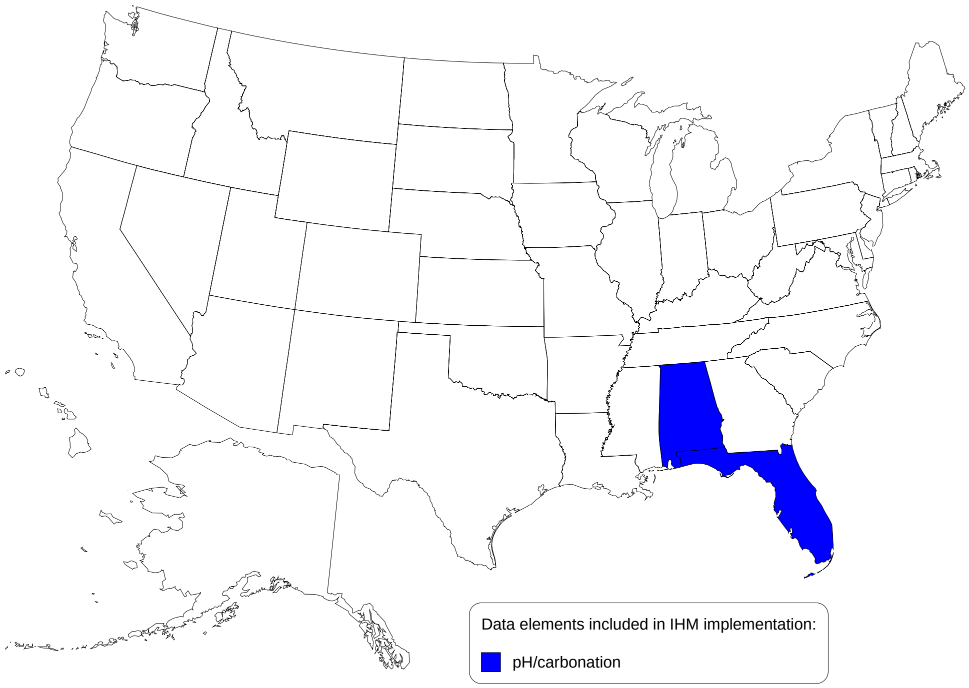

Data elements included in IHM implementation:
Temperature and thermal effects

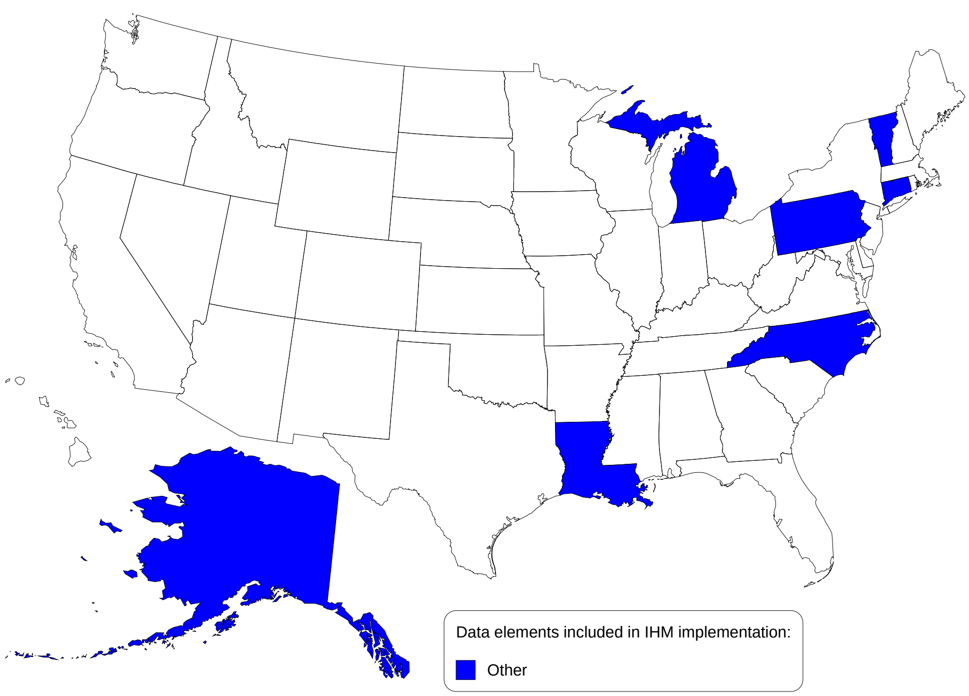

Data elements included in IHM implementation:
Noise/sound


Data elements included in IHM implementation:
Moisture/ice detection

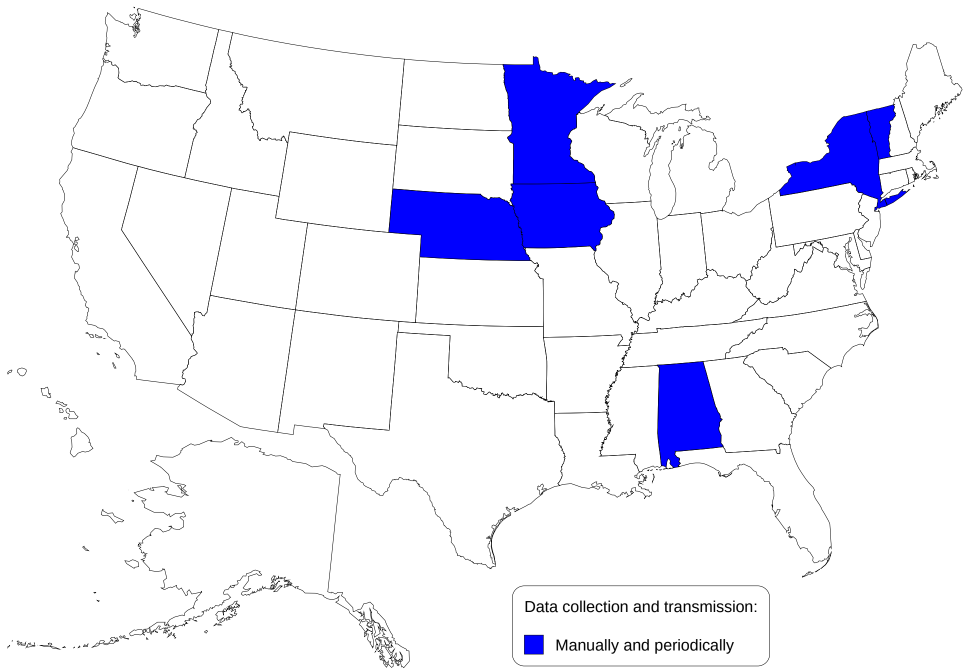

Data elements included in IHM implementation:
Chloride ion penetration

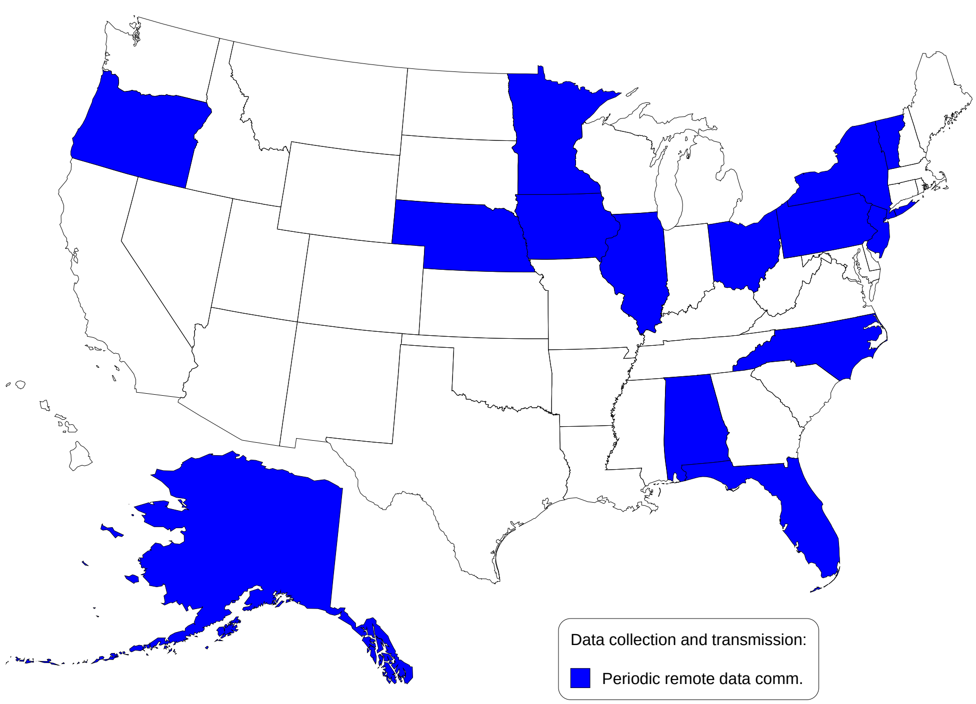

Data elements included in IHM implementation:
Air quality

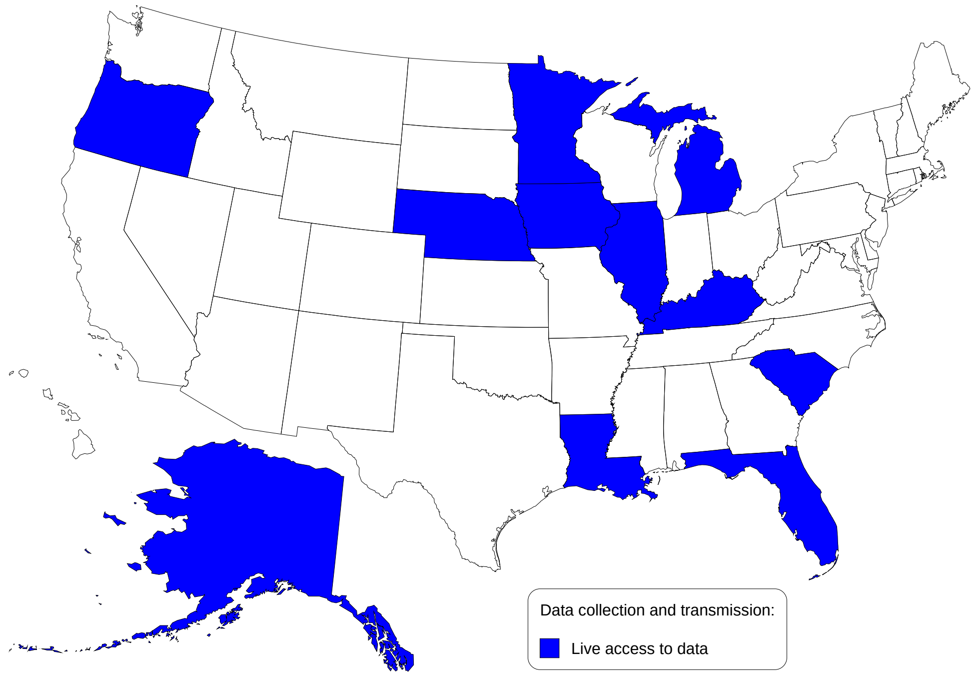

Data elements included in IHM implementation:
pH/carbonation

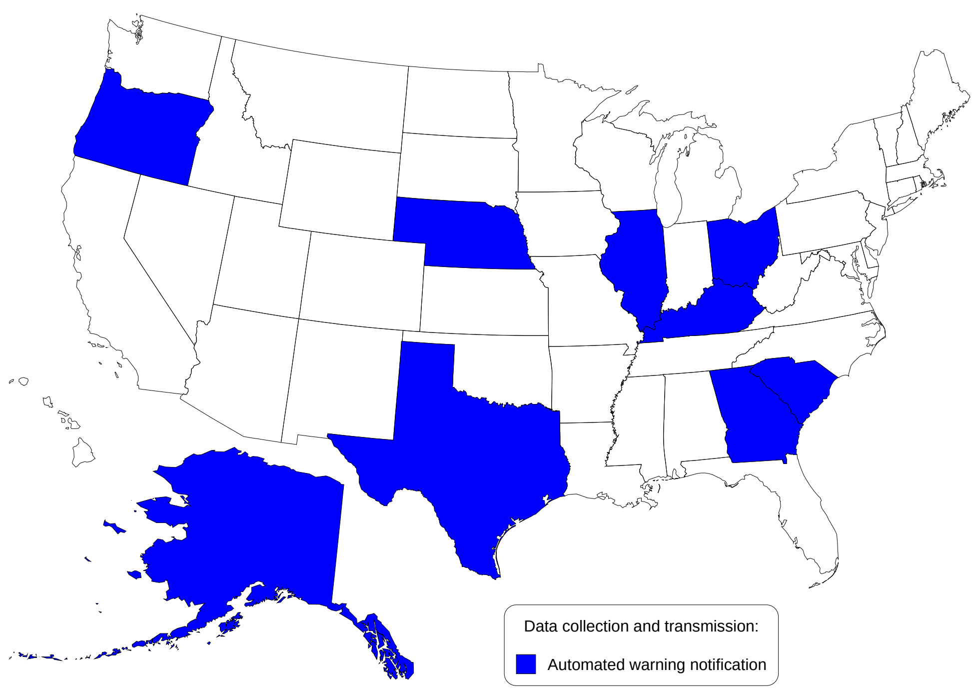

Data elements included in IHM implementation:
Other

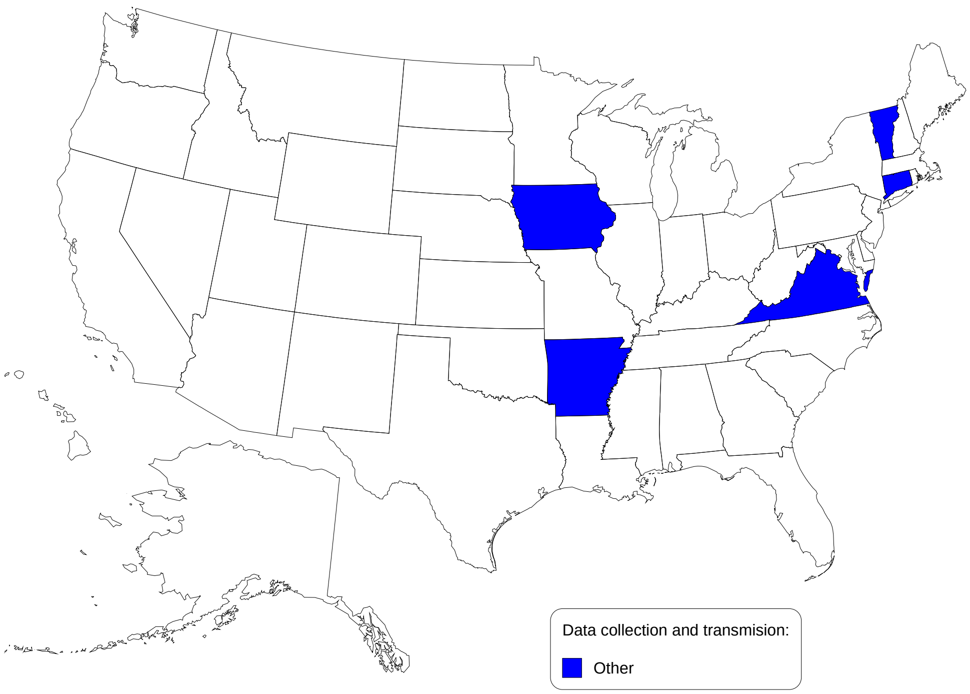
5. How were data collected and transmitted?



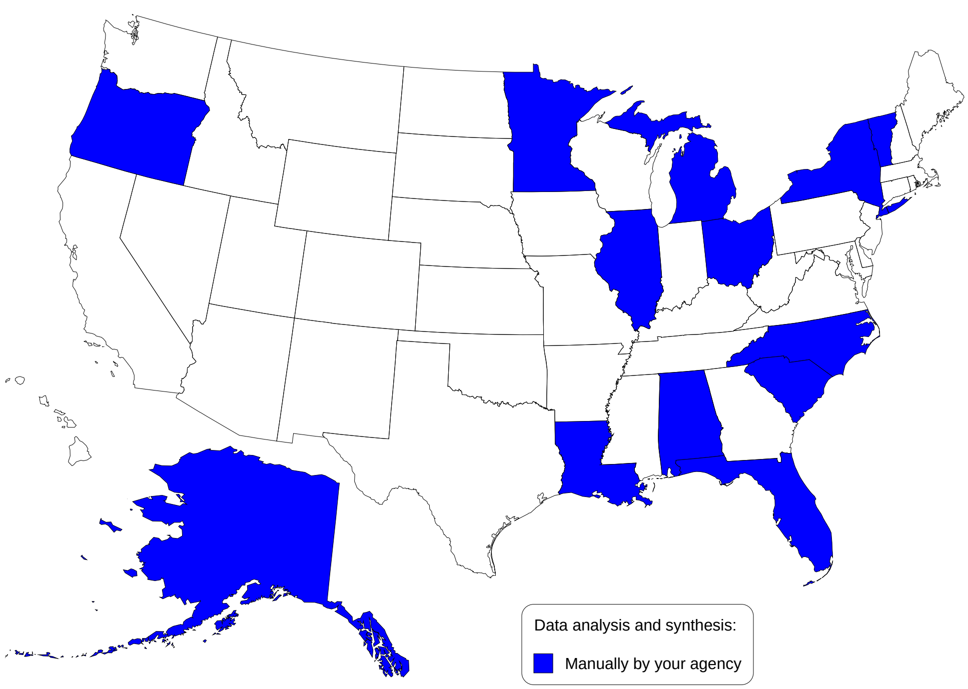


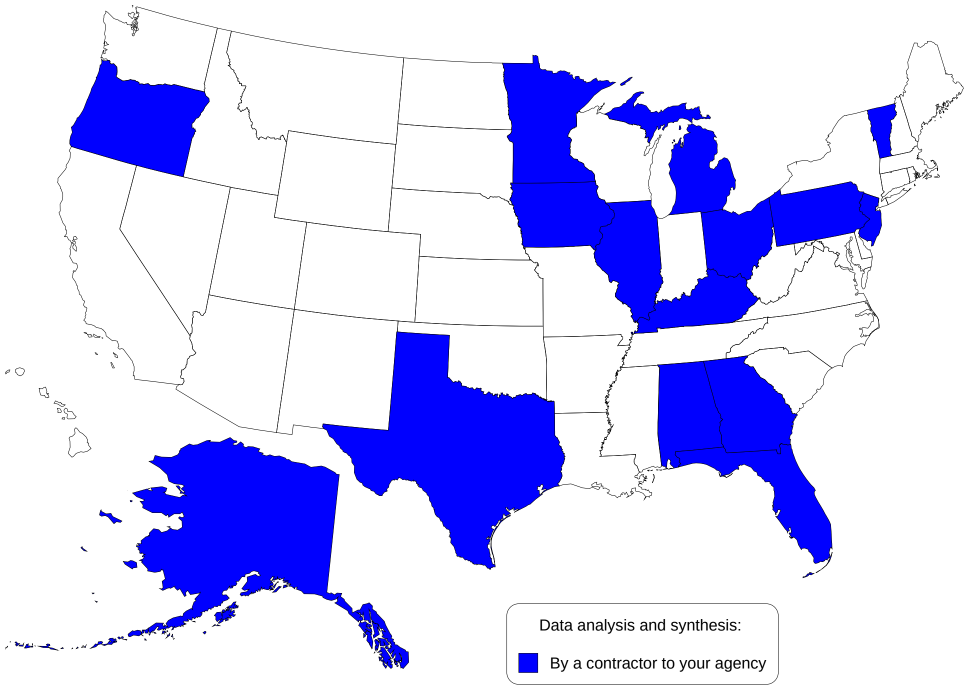

Data collection and transmission:
Live access to data

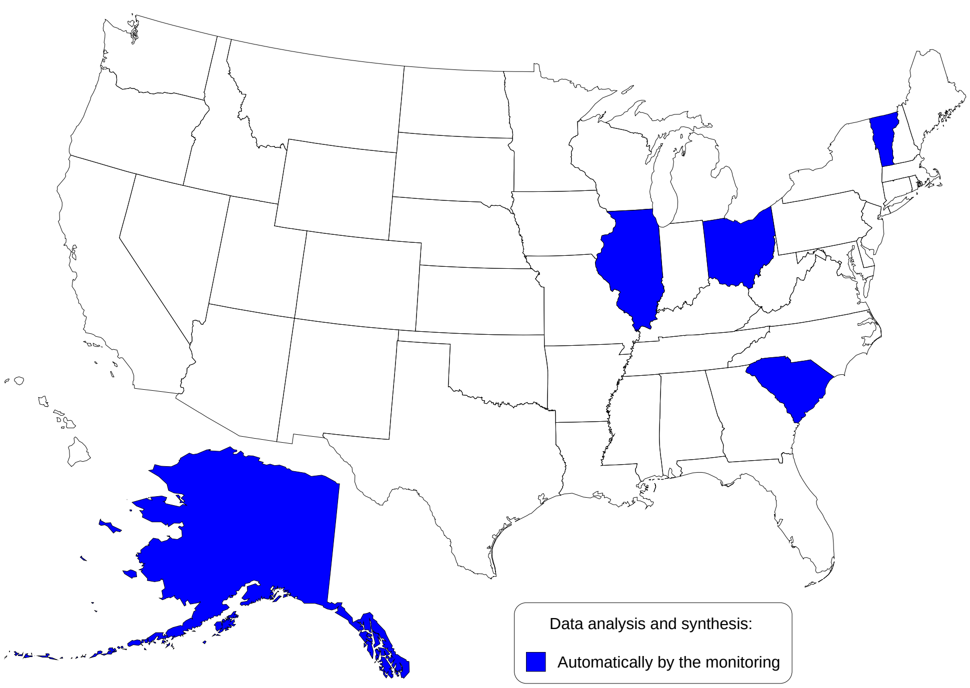

Data collection and transmission:
Automated warning notification

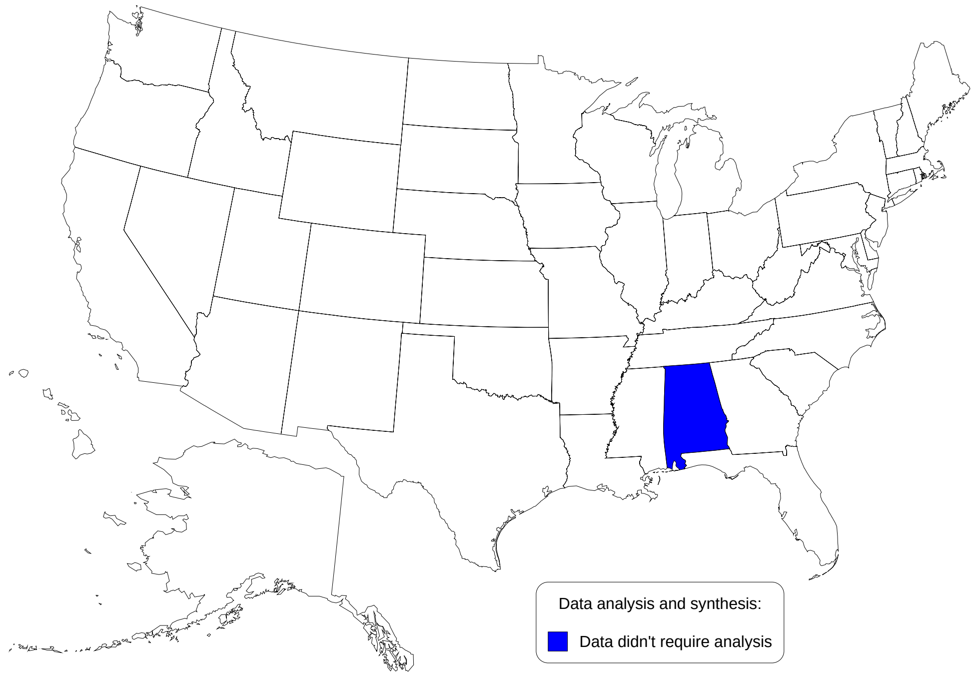


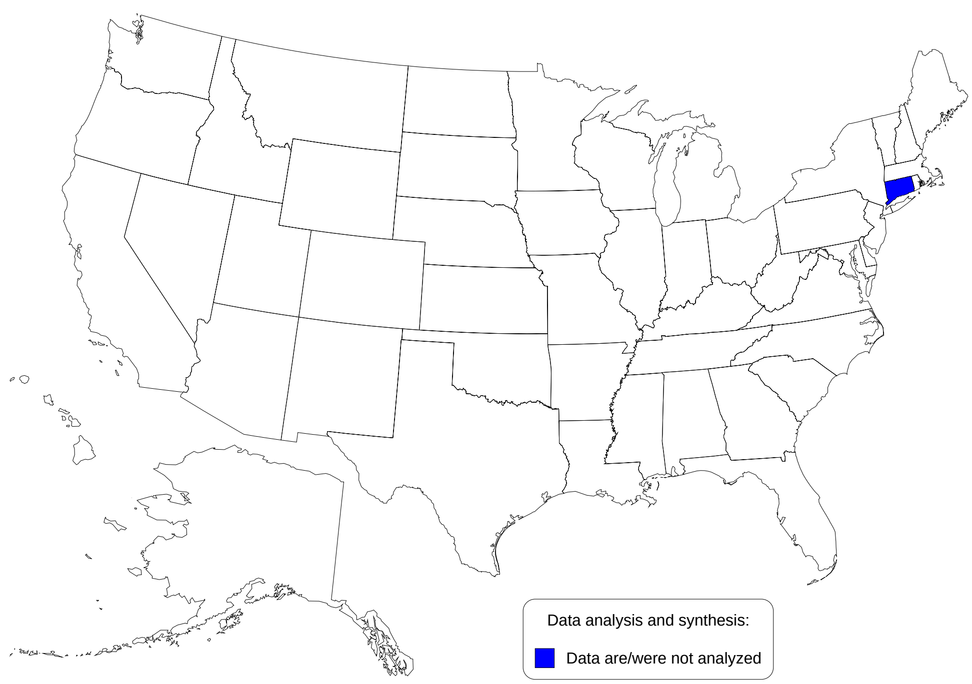
6. How were data analyzed and synthesized?

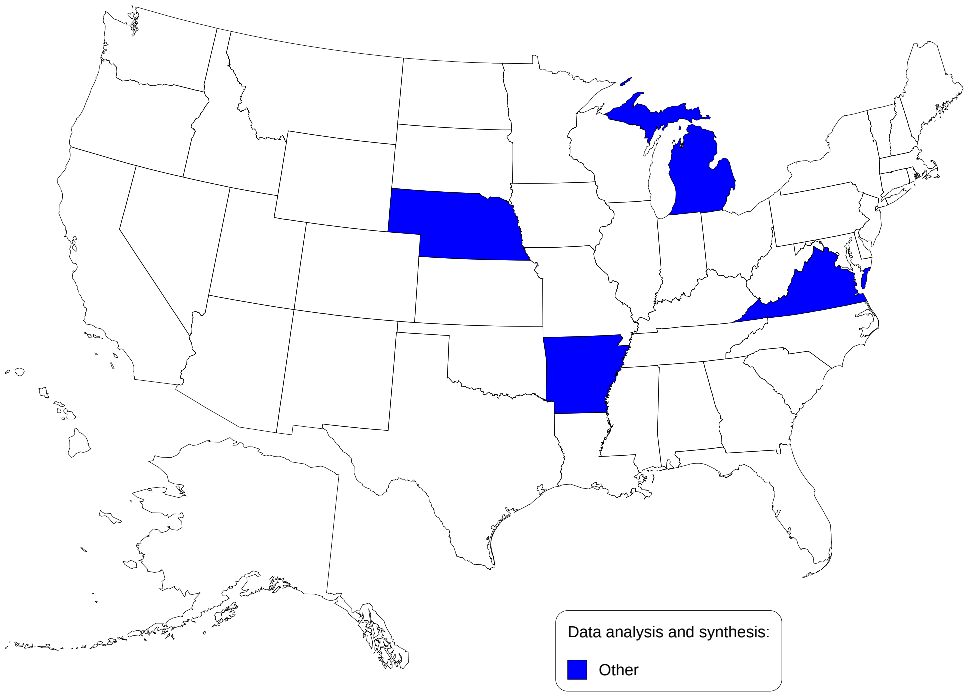



Data analysis and synthesis:
By a contractor to your agency

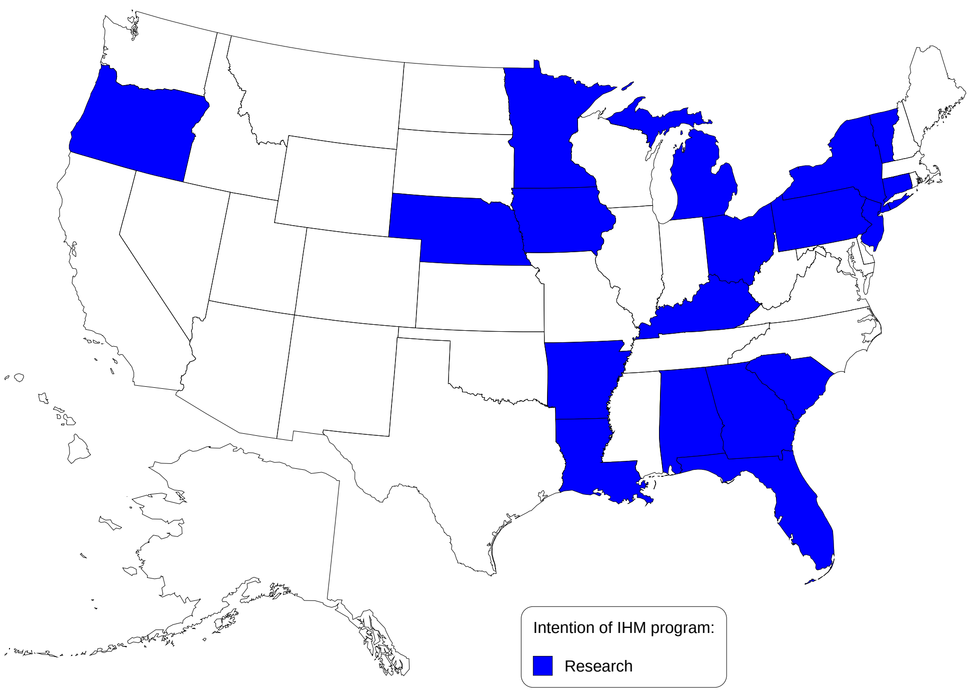

Data analysis and synthesis:
Automatically by the monitoring

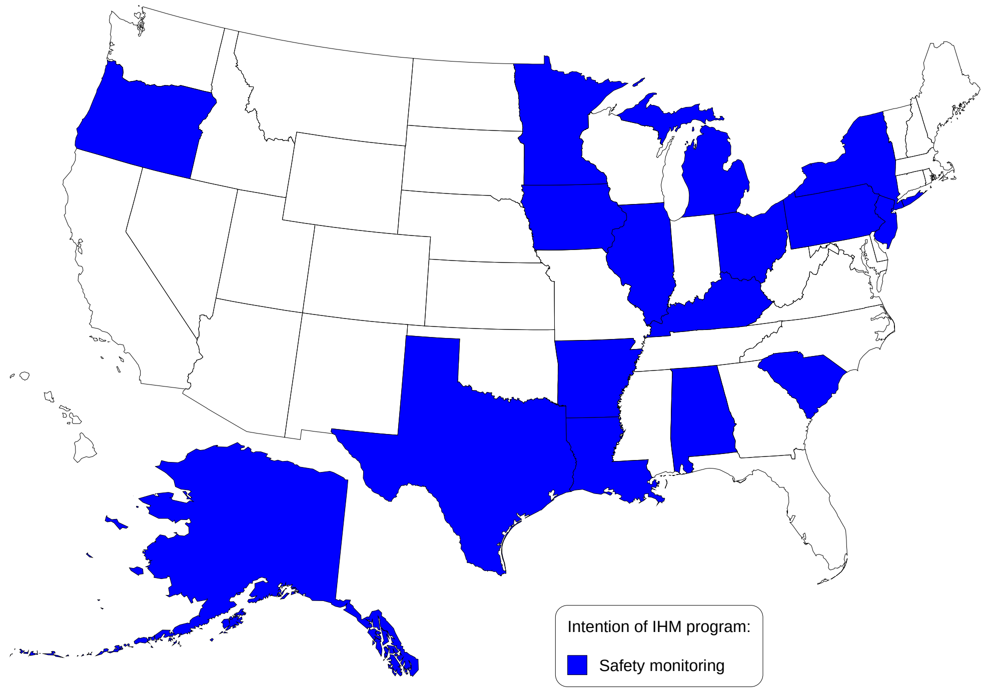

Data analysis and synthesis:
Data didn't require analysis

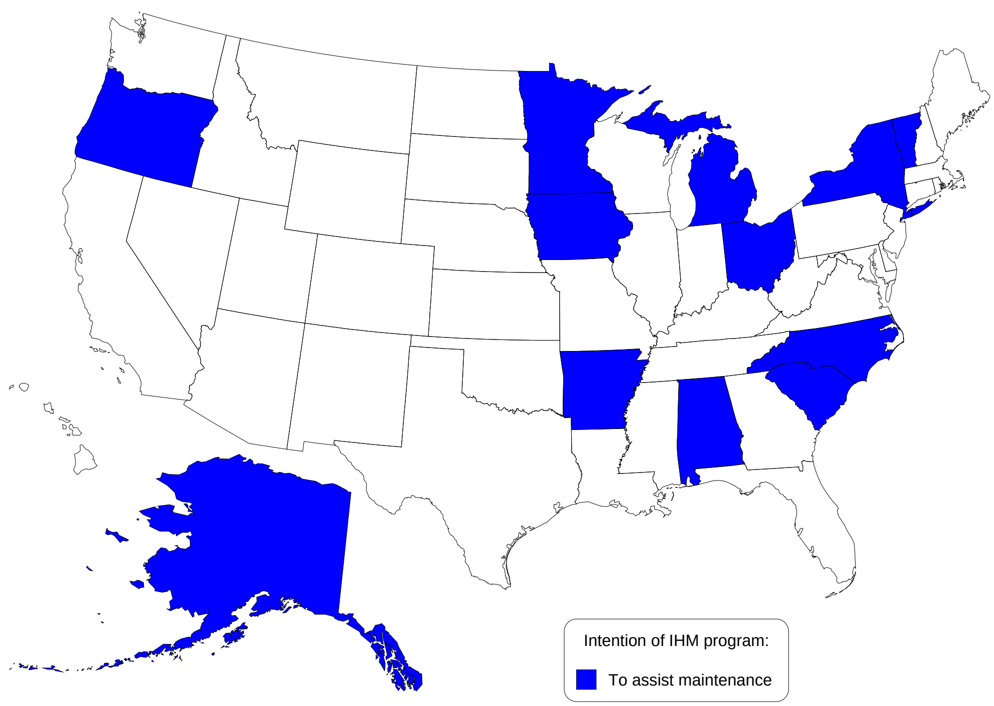

Data analysis and synthesis:
Data are/were not analyzed

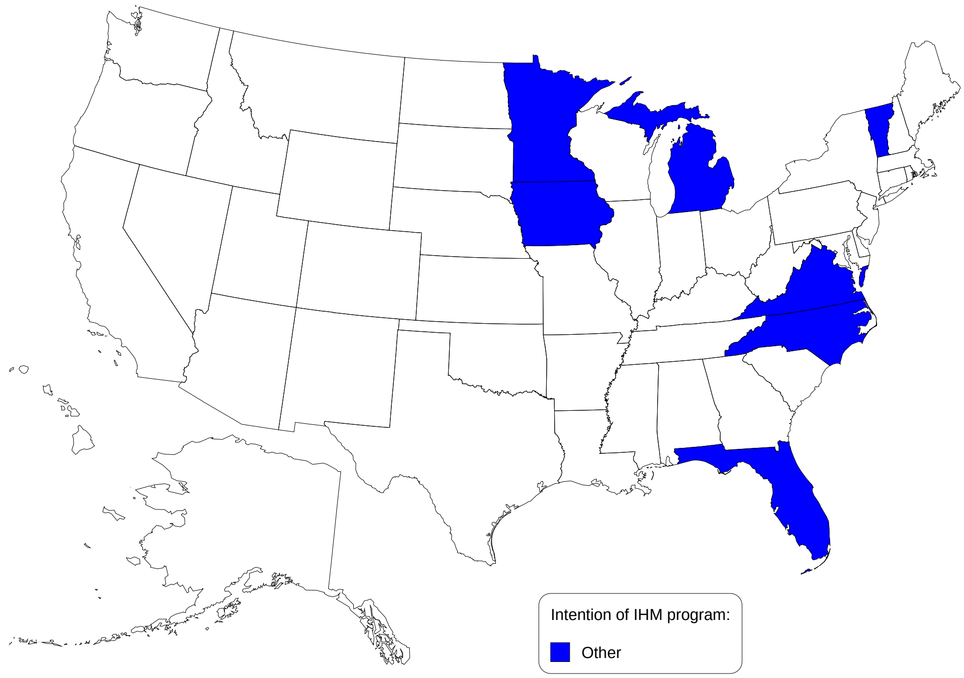


7. What was the intent of the IHM program?

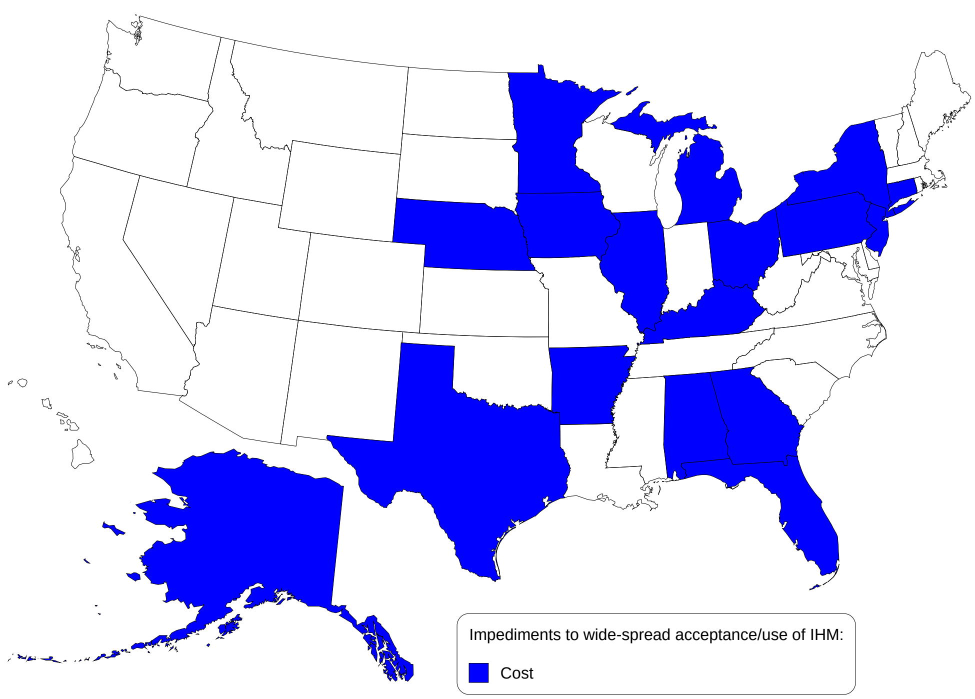


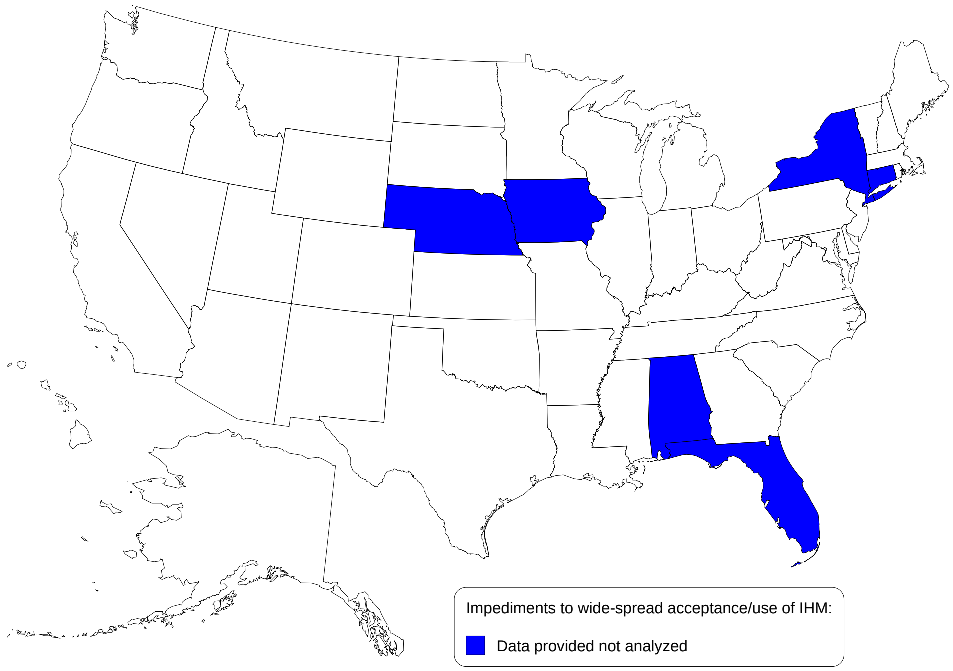

Intention of IHM program:
Safety monitoring

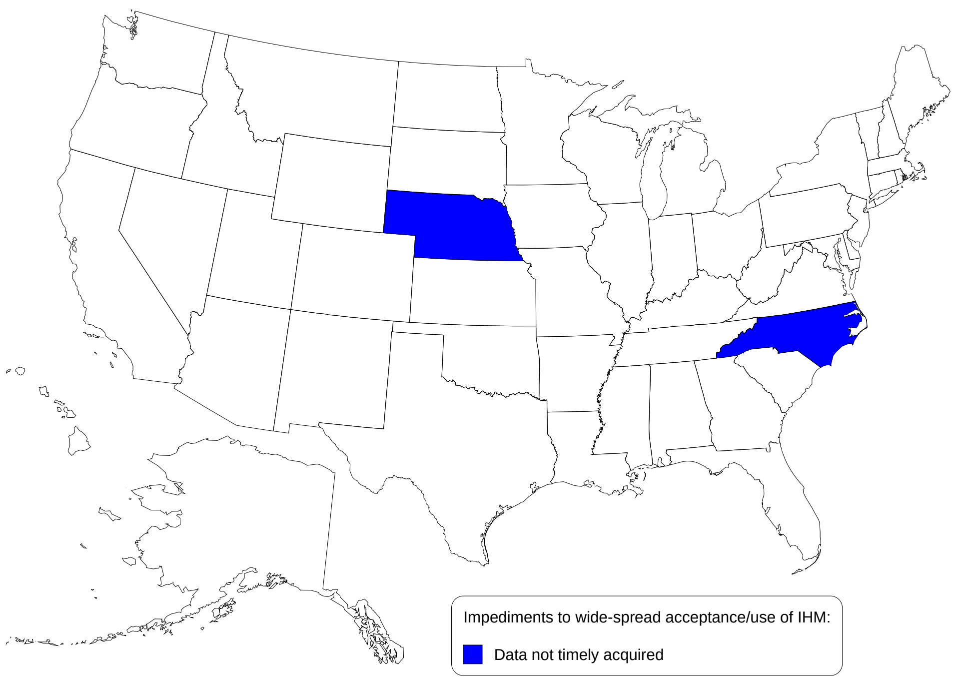

Intention of IHM program:
To assist maintenance

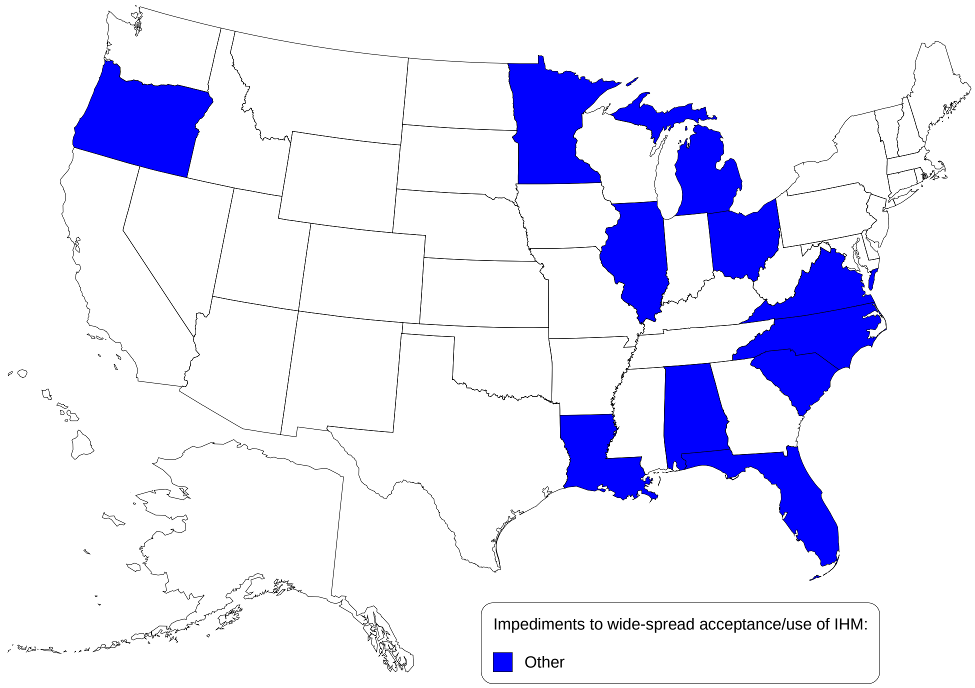


8. What are/were the most important impediments to wide-spread acceptance/use of your IHM program?

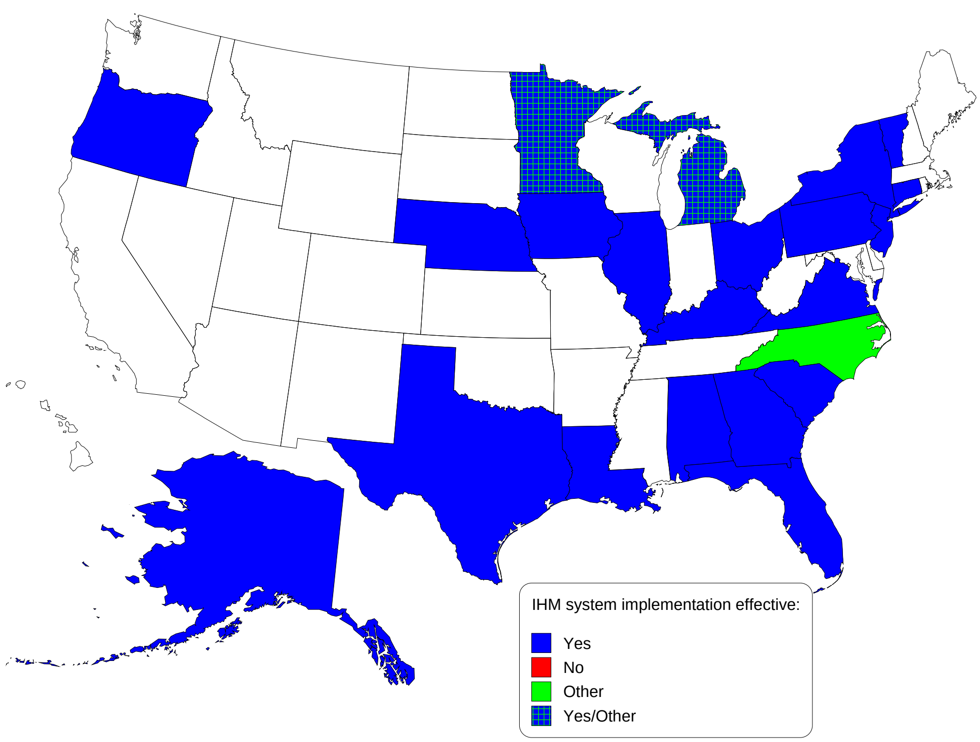


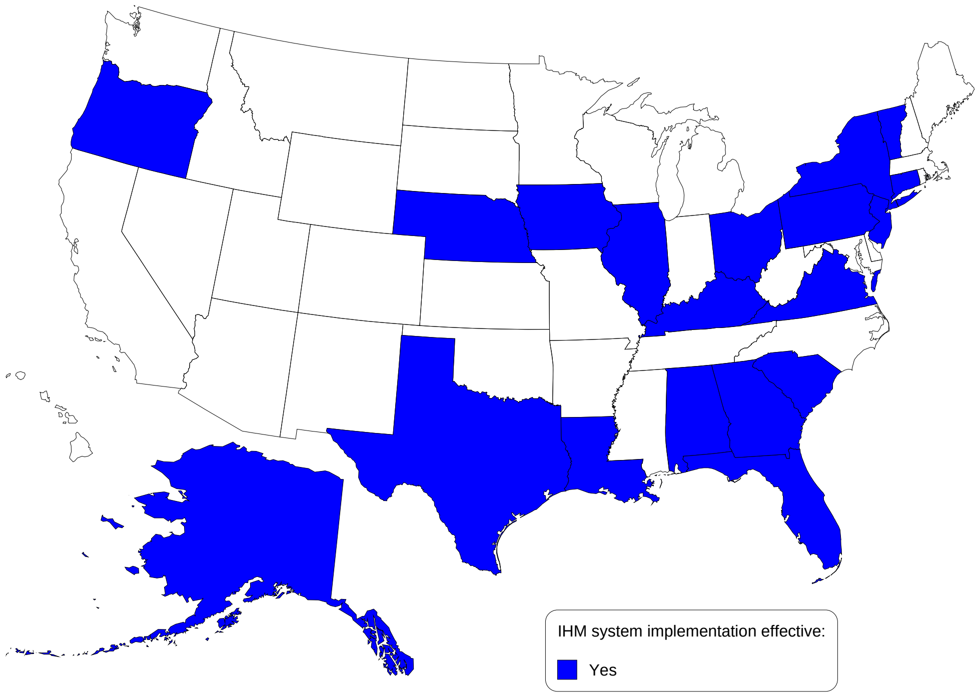

Impediments to wide-spread acceptance/use of IHM:
Data provided not analyzed

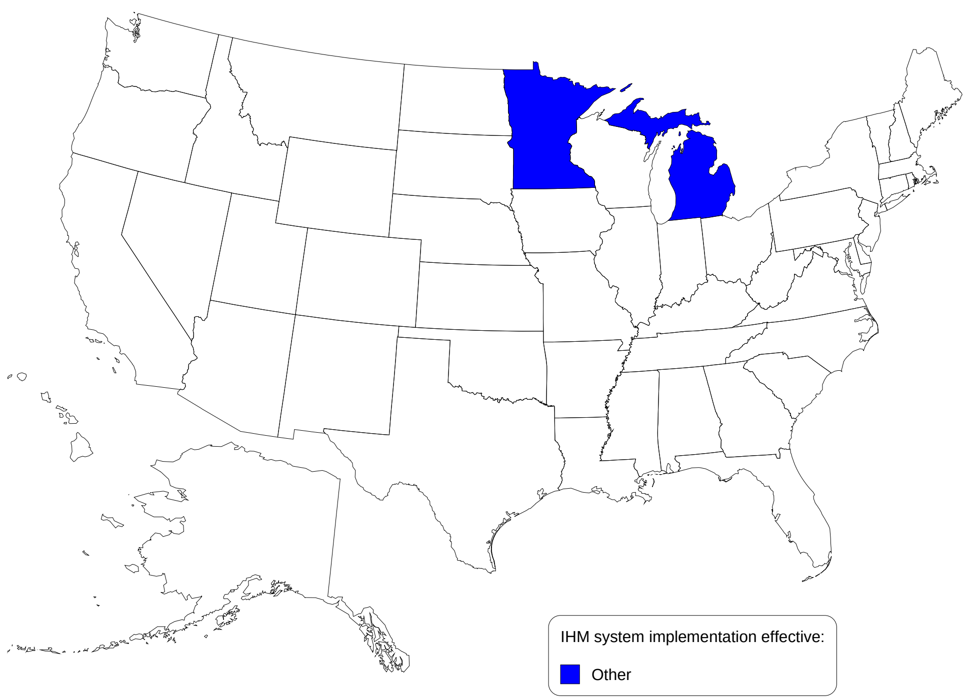

Impediments to wide-spread acceptance/use of IHM:
Data not timely acquired



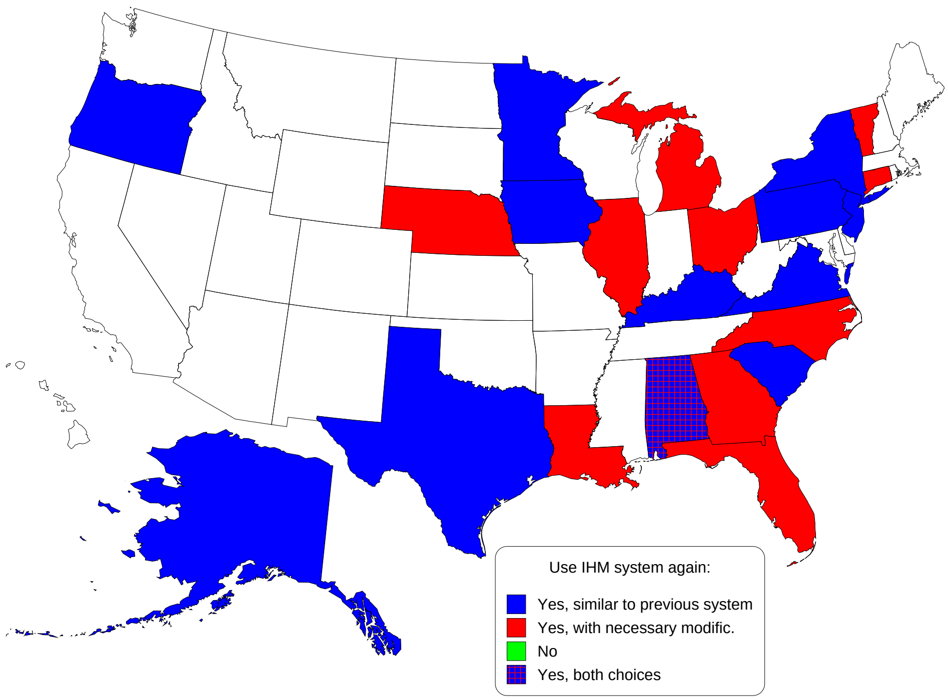
9. **Do you consider your implementation of an IHM system effective?**




IHM system implementation effective:
Yes


IHM system implementation effective:
Other

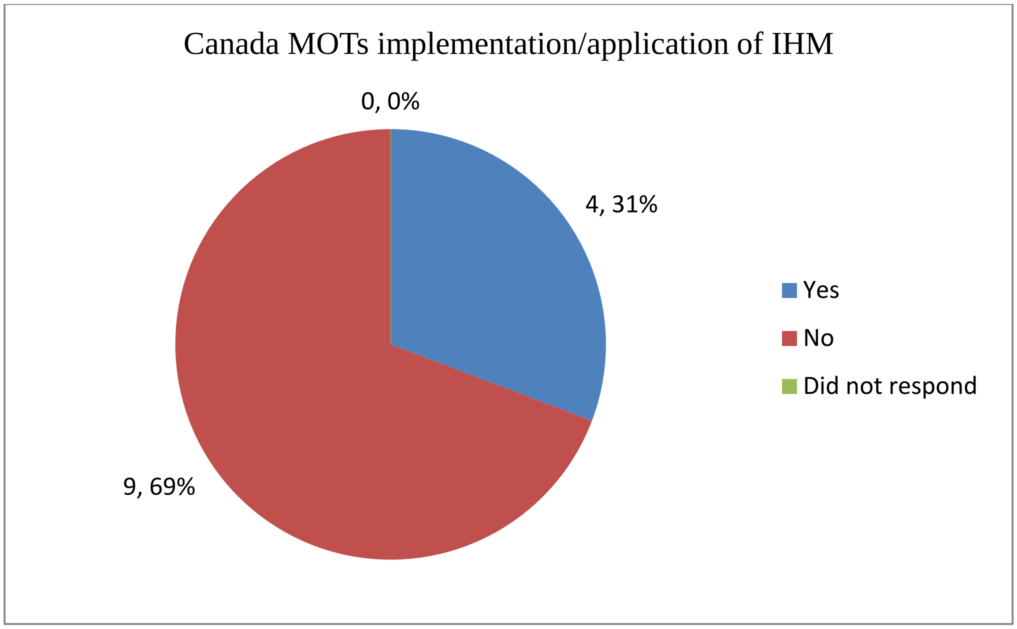
10. Will you use IHM again?



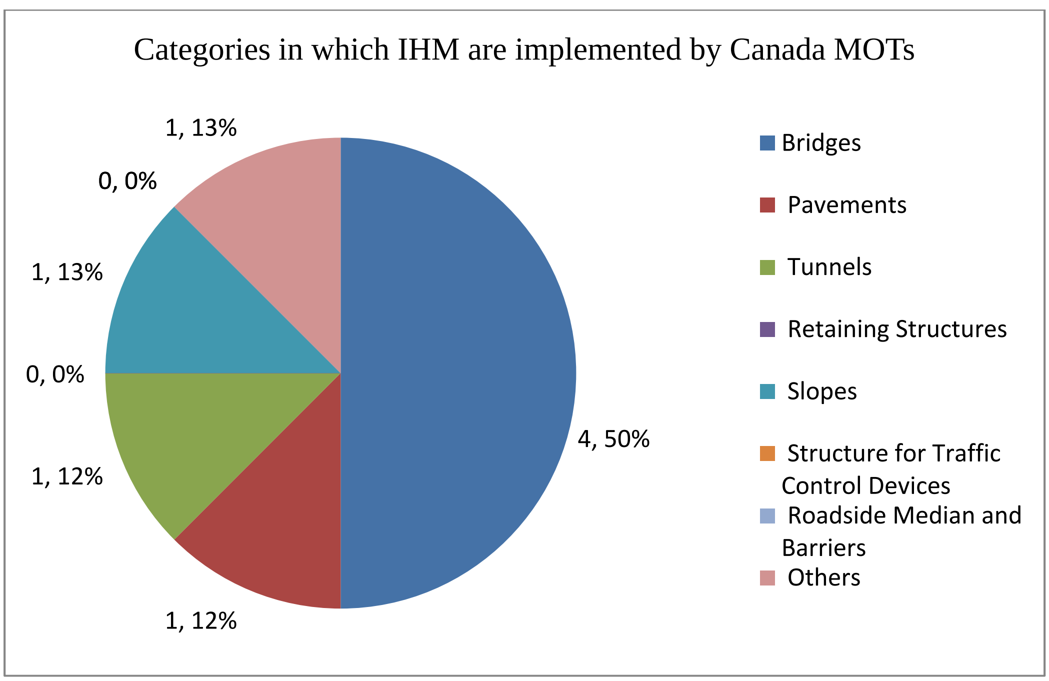
Appendix C

Canada MOT's survey pie charts

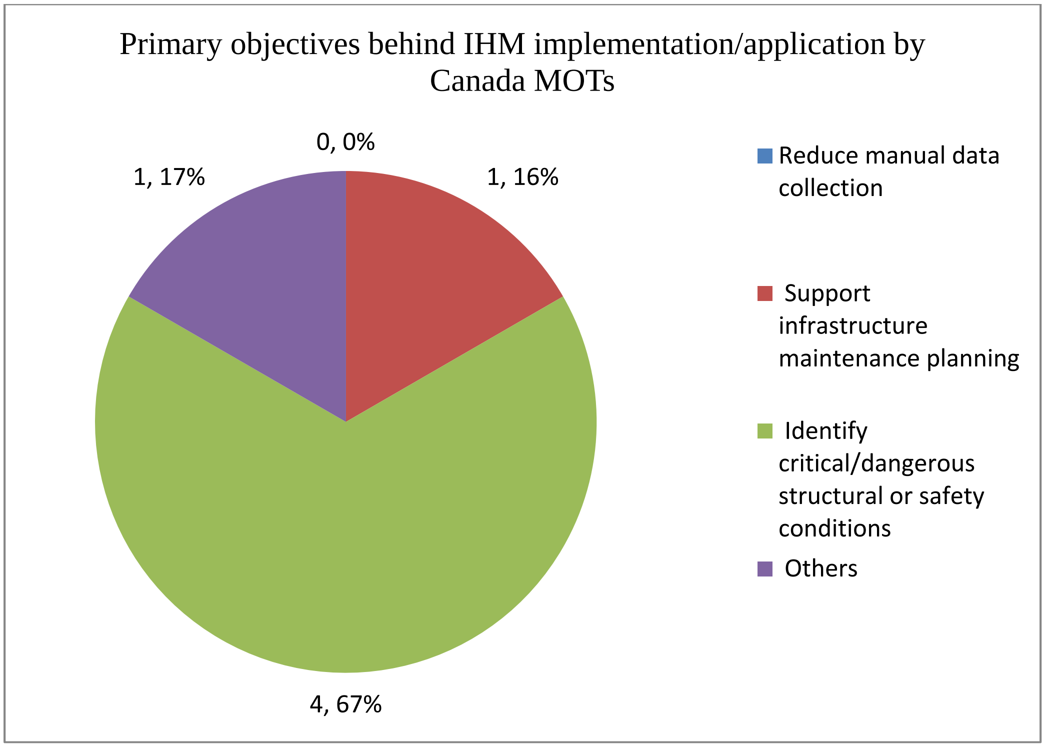
1. **Are there any Infrastructure Health Monitoring (IHM) applications for transportation infrastructure that have been implemented or are currently being implementation in your agency of which you or someone you know are knowledgeable about?**



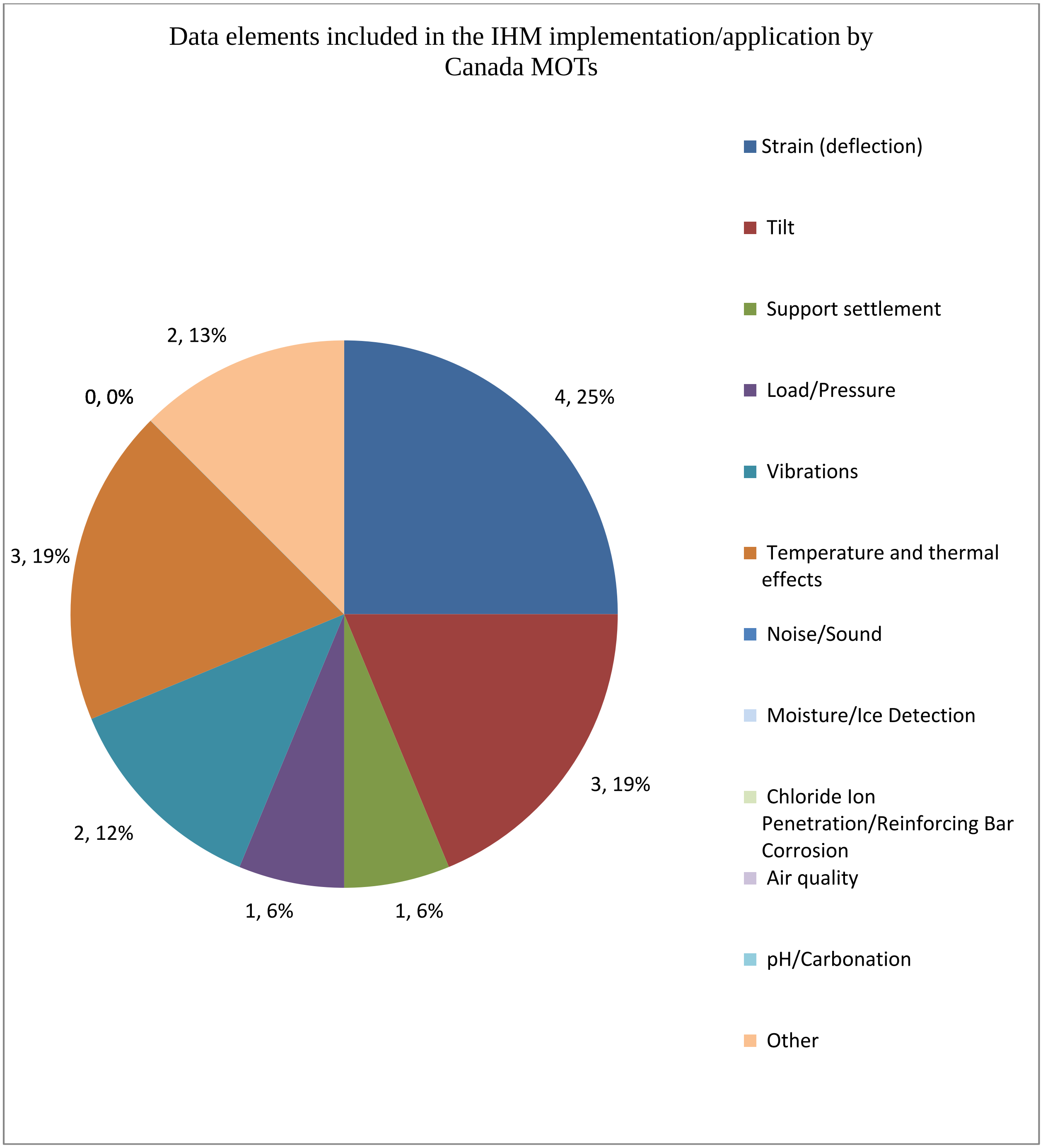
2. **Categories of transportation infrastructure for which IHM systems are implemented.**



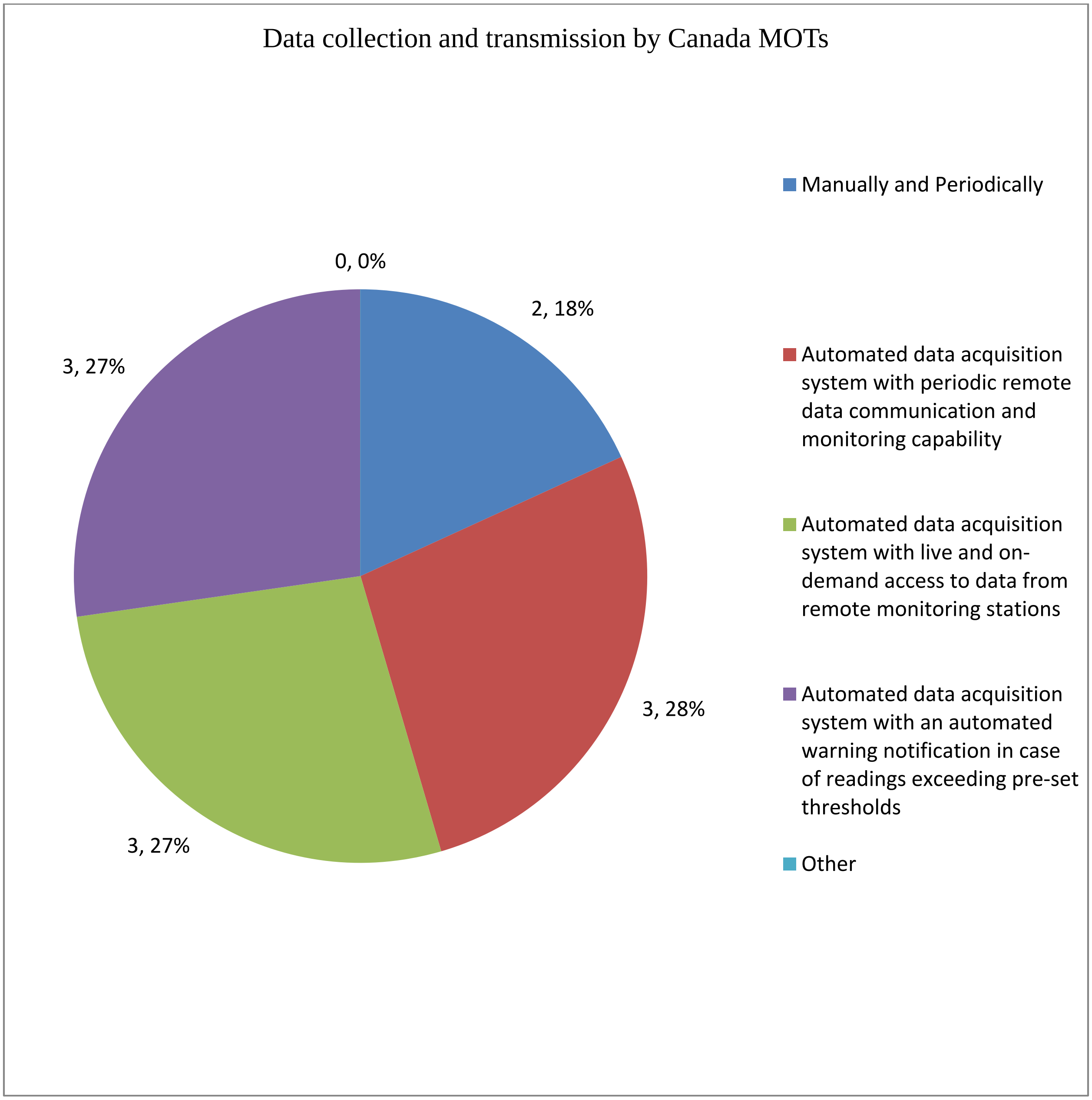
3. **What are/were the primary objectives behind your IHM implementation?**



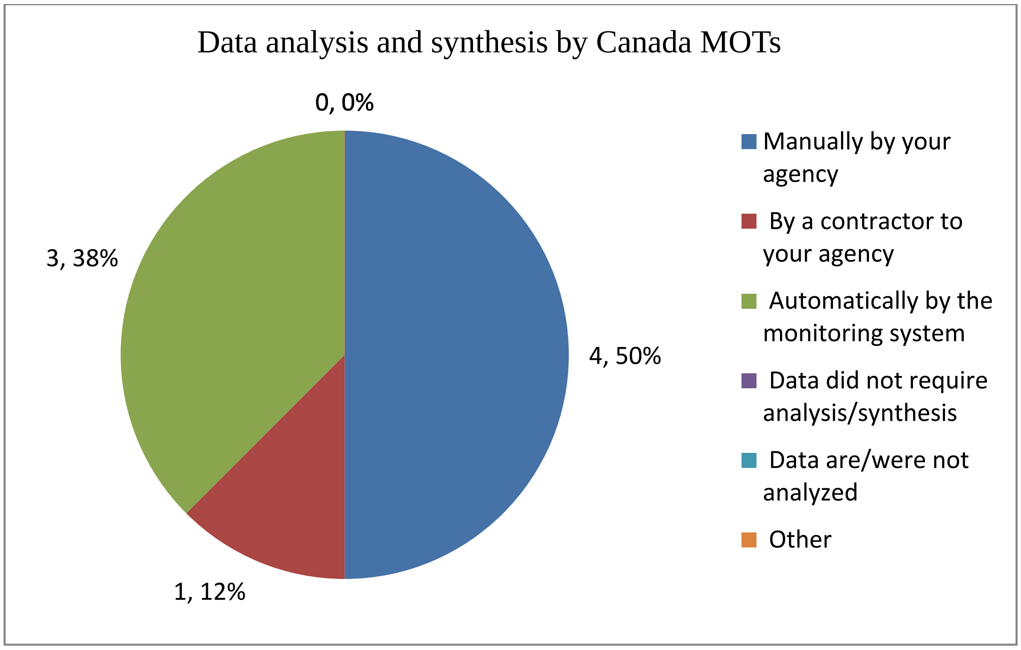
4. Which data elements were included in your IHM implementation?



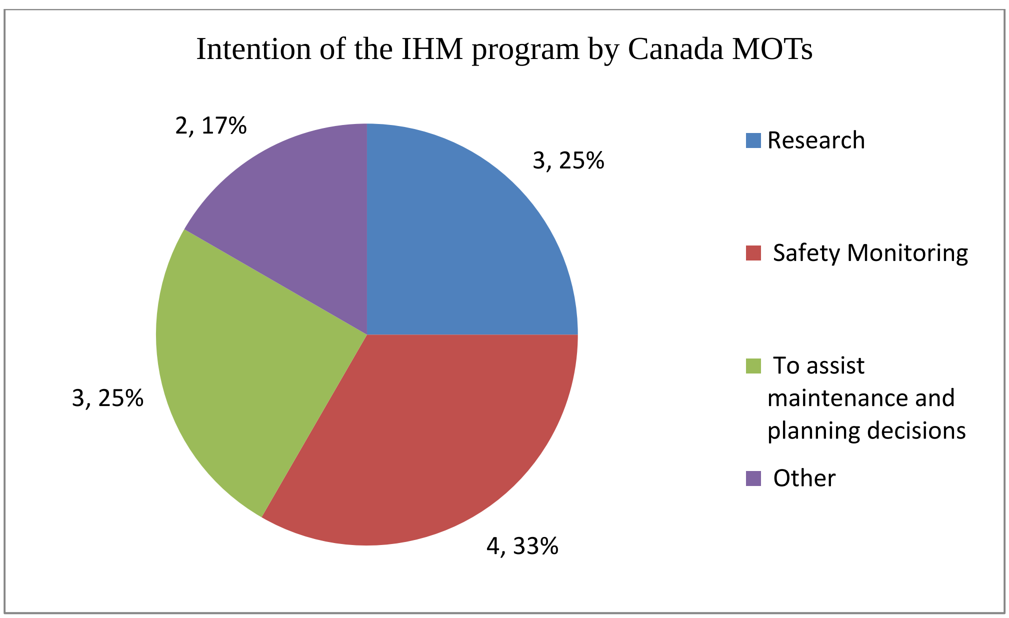
5. How were data collected and transmitted?



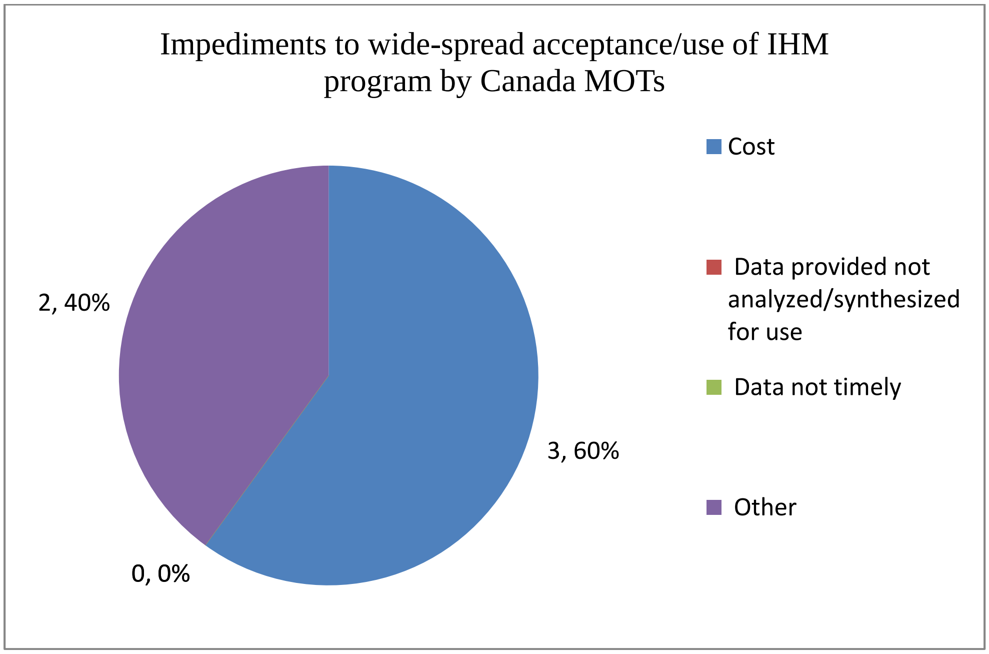
6. **How were the data analyzed and synthesized?**



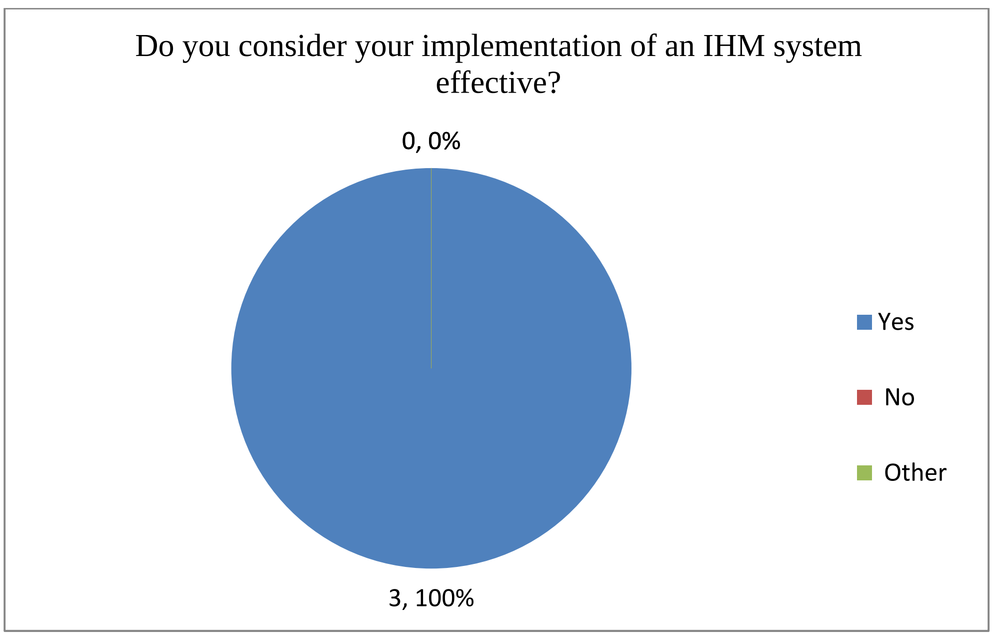
7. **What was the intent of the IHM programs?**



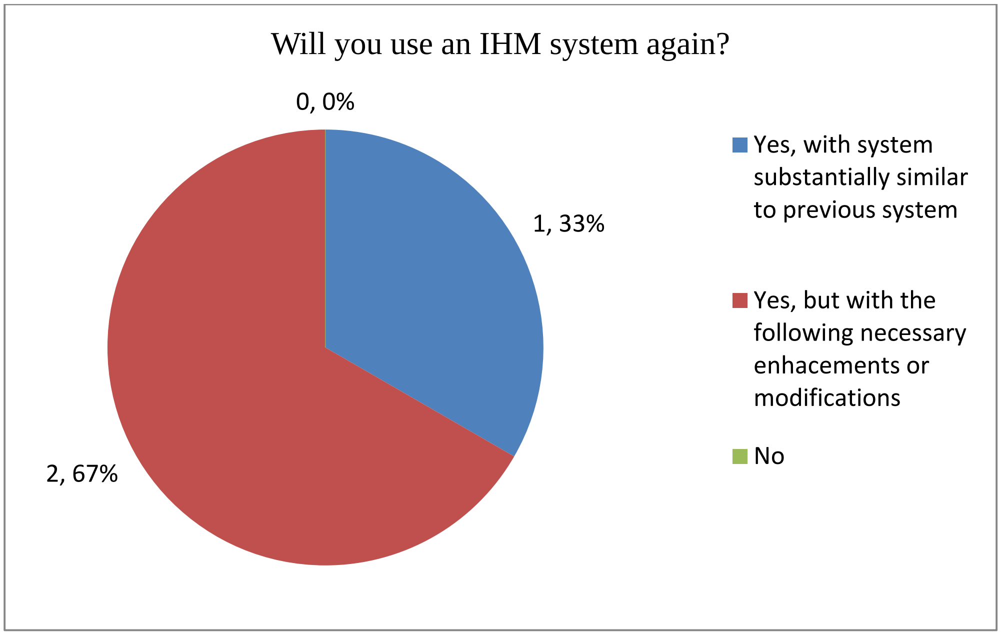
8. What are/were the most important impediments to wide-spread acceptance/use of your IHM program?



9. Do you consider your implementation of an IHM system effective?



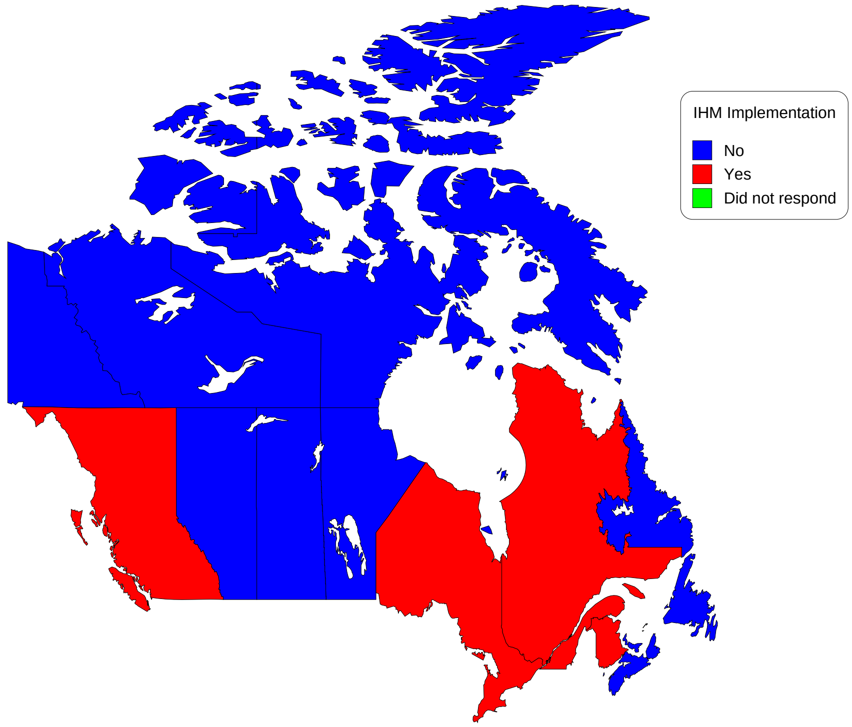
10. Will you use an IHM system again?



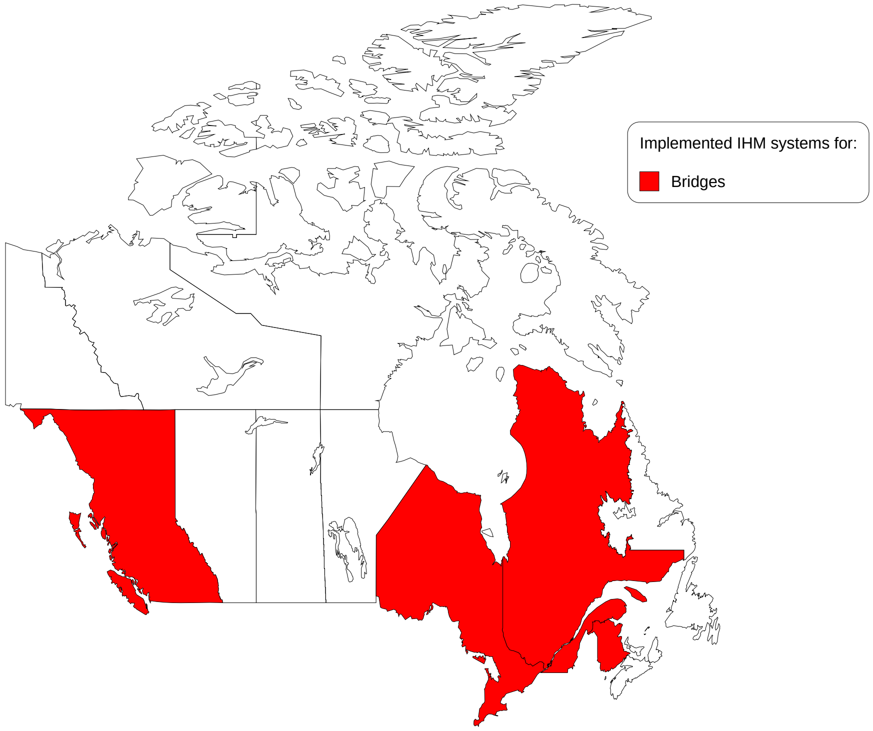
Appendix D

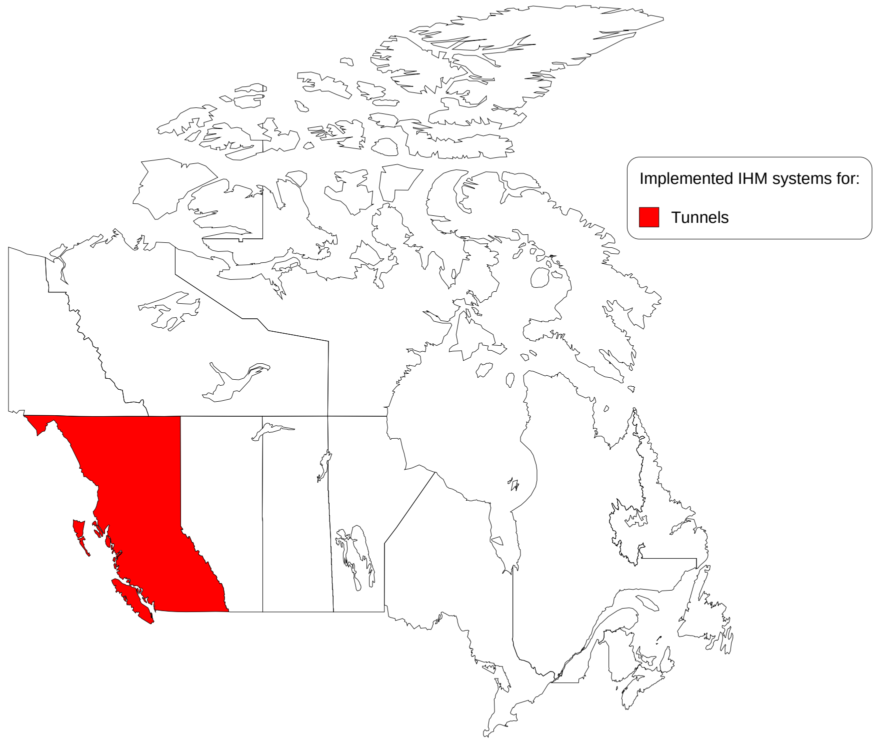
Canada MOTs survey maps

1. **Are there any Infrastructure Health Monitoring (IHM) applications for transportation infrastructure that have been implemented or are currently being implemented in your agency of which your or someone you know are knowledgeable about?**



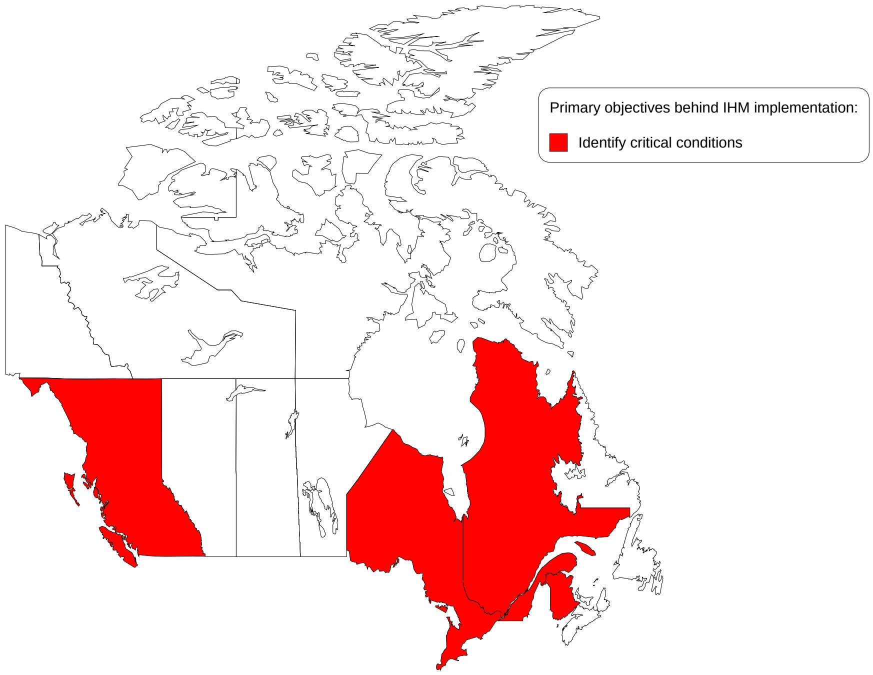
2. Categories of transportation infrastructure for which IHM systems are implemented.




Implemented IHM systems for:
Tunnels

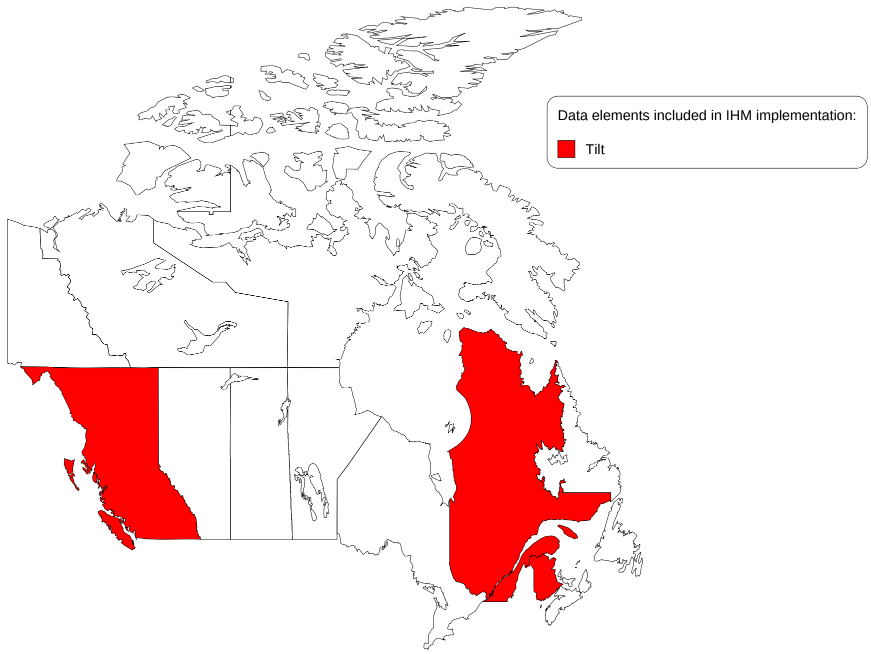

Implemented IHM systems for:
Slopes

3. What are/were the primary objectives behind your IHM implementation?

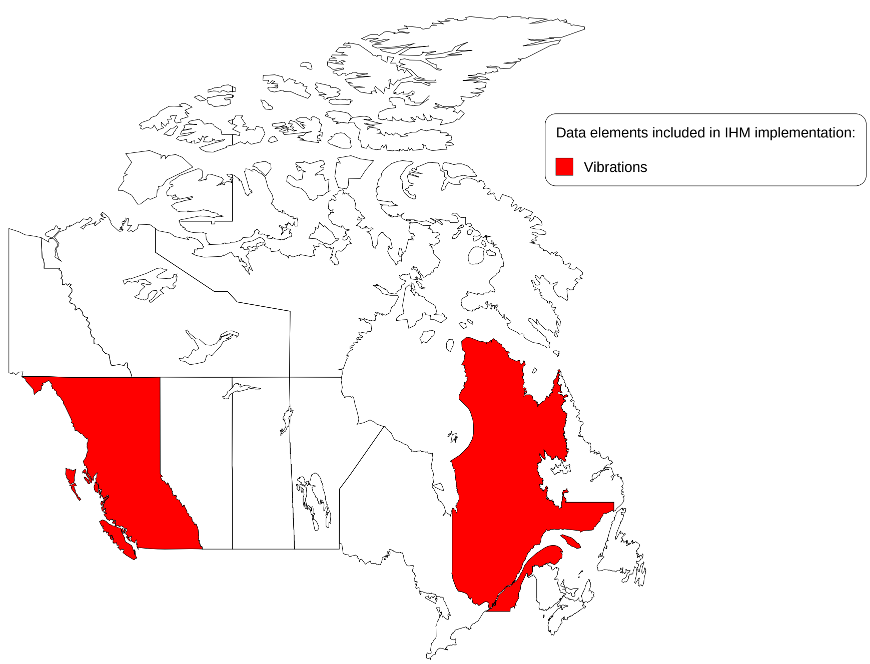

Primary objectives behind IHM implementation:
Identify critical conditions


Primary objectives behind IHM implentation:
Other

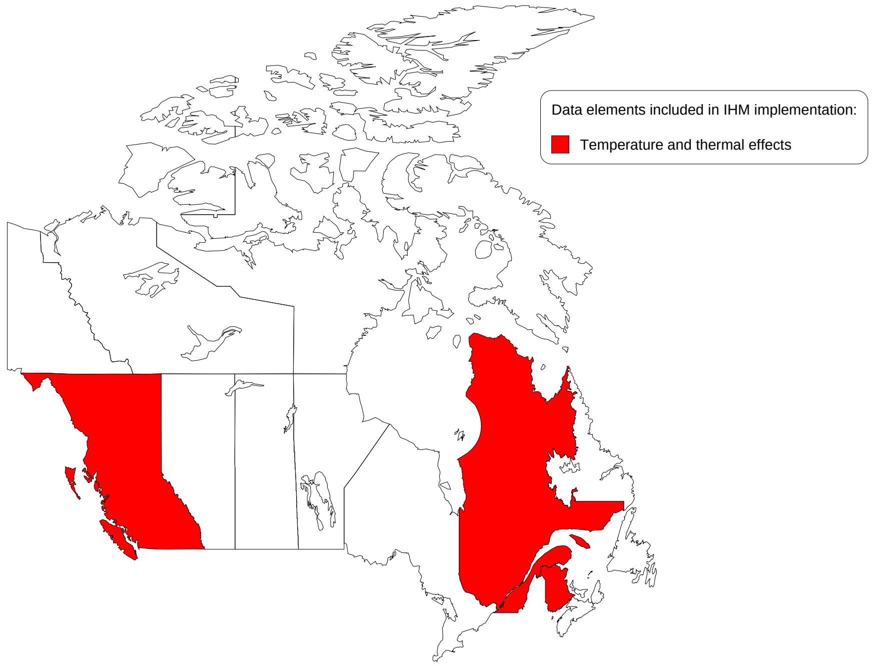
4. Which data elements are objectives behind your IHM implementation?



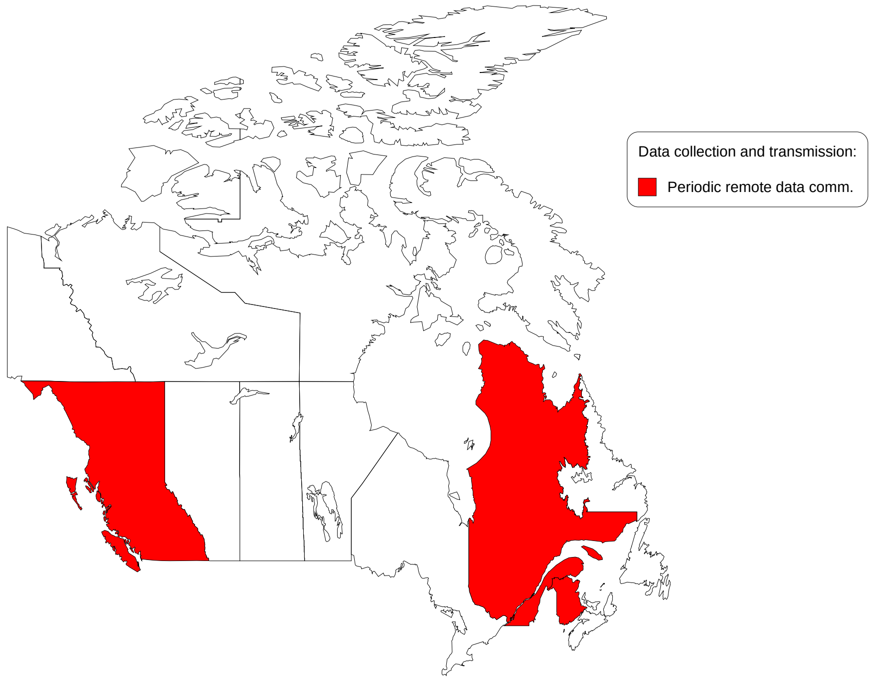
Data elements included in IHM implementation:
Load/pressure



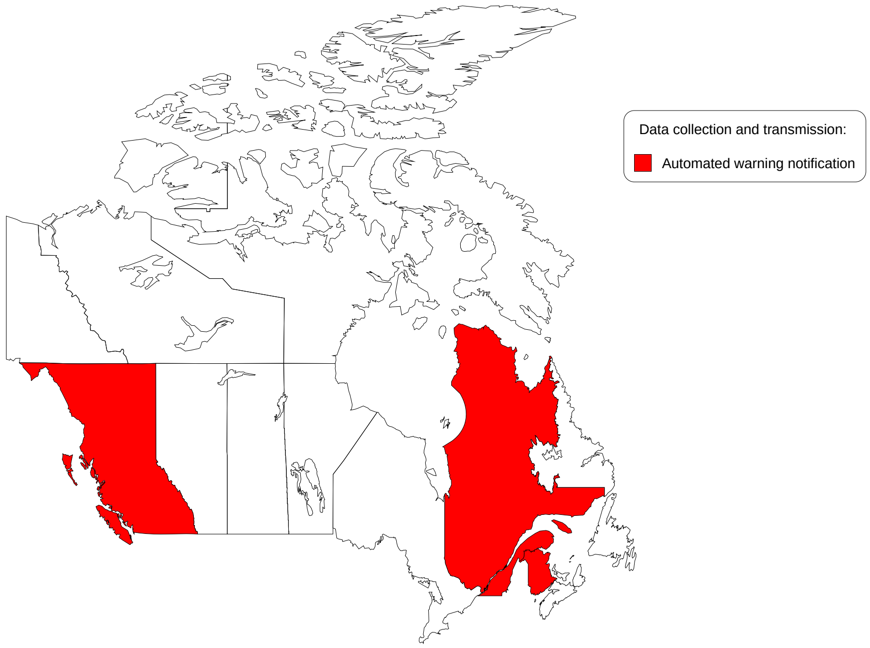
Data elements included in IHM implementation:
Vibrations



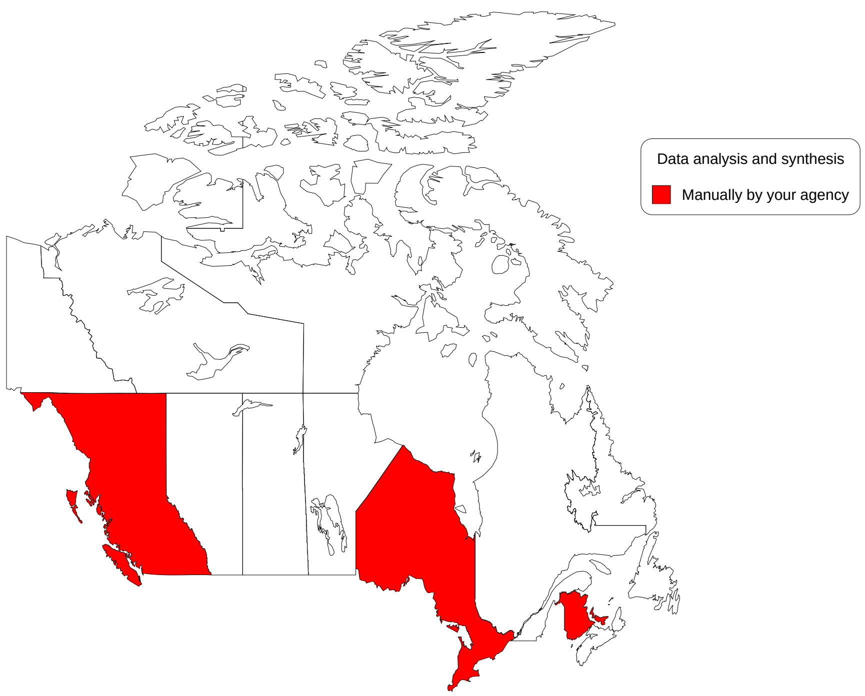
5. How were data collected and transmitted?

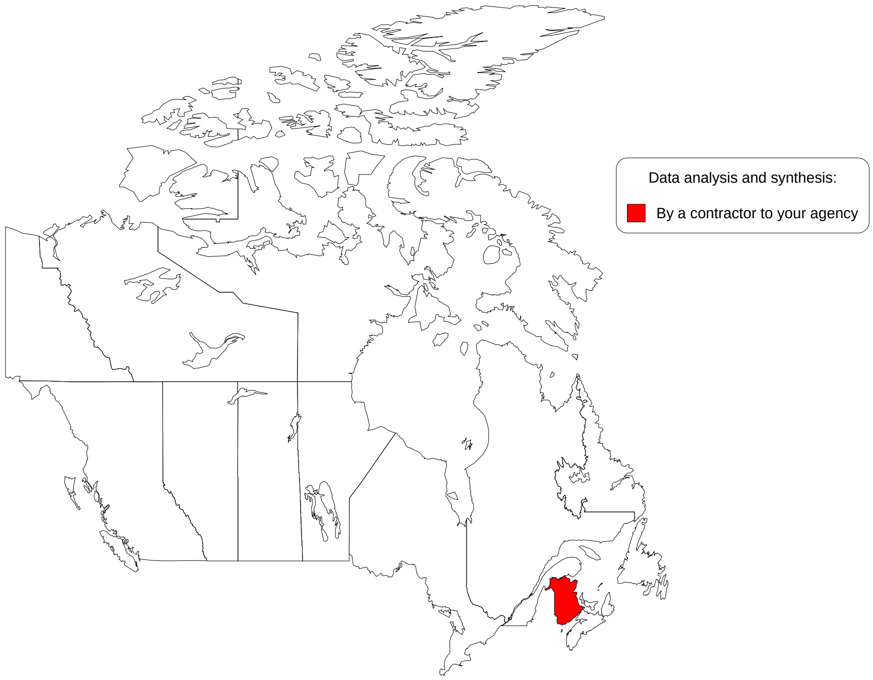

Data collection and transmission:
Periodic remote data comm.


Data collection and transmission:
Live access to data



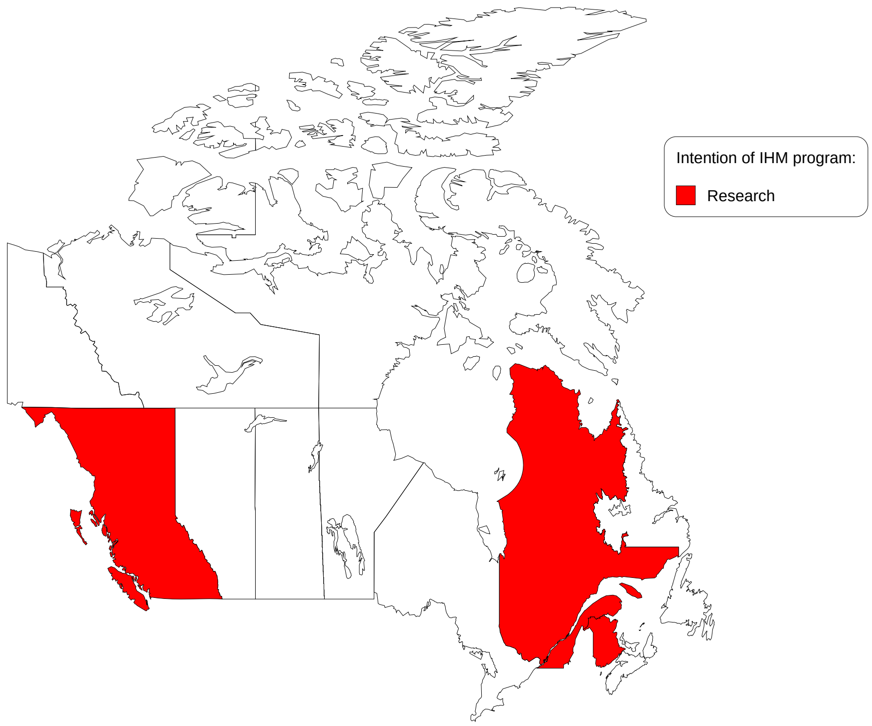
6. How were data analyzed and synthesized?

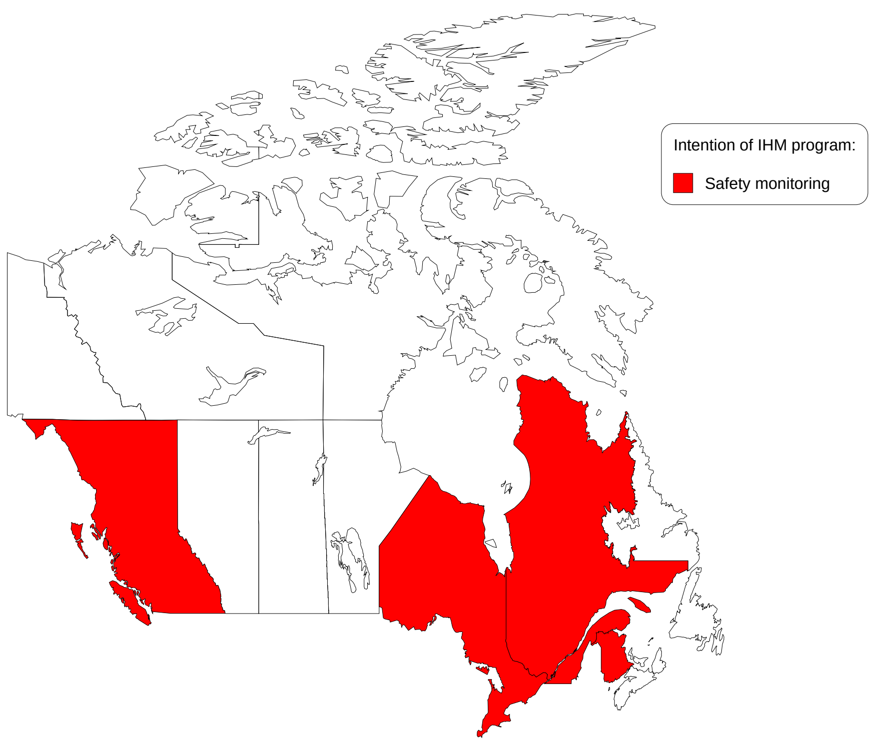



Data analysis and synthesis:
By a contractor to your agency


Data analysis and synthesis:
Automatically by the monitoring

7. **What was the intent of the IHM program?**



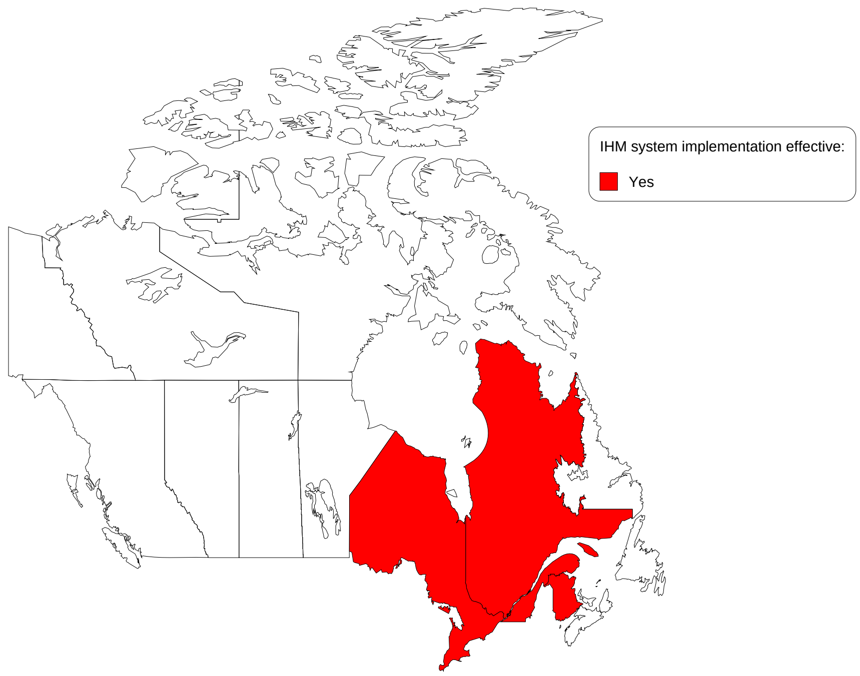



Intention of IHM program:
To assist maintenance

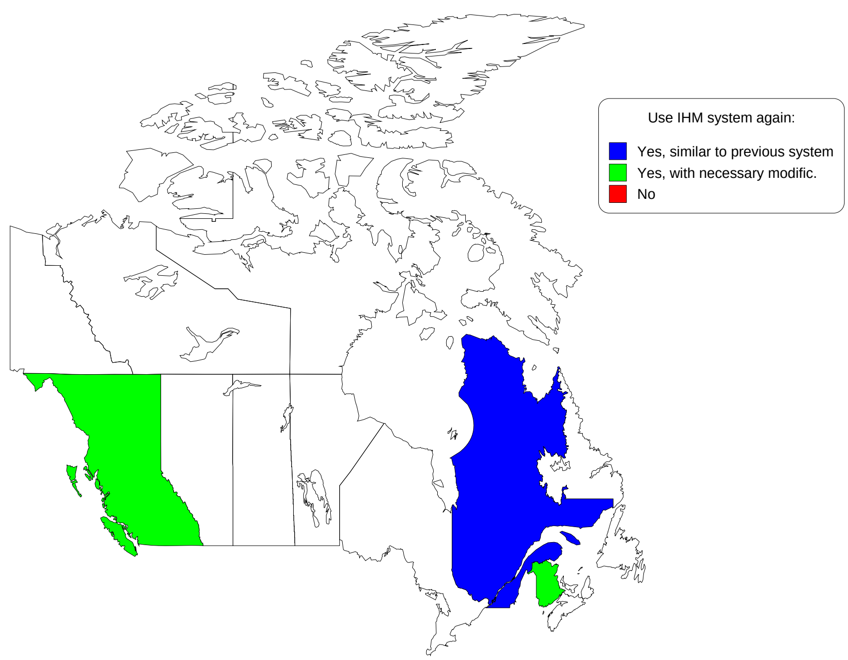

Intention of IHM program:
Other

8. What are/were the most important impediments to wide-spread acceptance/use of your IHM program?

9. Do you consider your implementation of an IHM system effective?



10. Will you use IHM again?



NATIONAL CENTER FOR FREIGHT & INFRASTRUCTURE RESEARCH & EDUCATION

CFIRE

University of Wisconsin-Madison
Department of Civil and Environmental Engineering
1410 Engineering Drive, Room 270
Madison, WI 53706
Phone: 608-263-3175
Fax: 608-263-2512
cfire.wistrans.org