Using Infrastructure Health Monitoring (IHM) to Assess the Impact of Climate Change on Civil Infrastructure

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Paper Prepared for Presentation
at the

MAINTENANCE & CONSTRUCTION TECHNICAL PAPER SESSION

Impact of Climate Change on Infrastructure Construction, Maintenance and Operations of the Annual Conference of the Transportation Association of Canada

Toronto, Ontario
September 21-23, 2008

MAINTENANCE & CONSTRUCTION TECHNICAL PAPER SESSION
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ABSTRACT

Climate change is creating a trend toward warming temperatures. As a result, temperate regions that currently experience freeze thaw cycles may experience fewer cycles in the future and regions currently experiencing deep seasonal or even permafrost conditions may expect thawing when previously they did not. These types of regions dominate Canada.

Since the performance of transportation infrastructure is impacted by both traffic loading and environmental factors, these factors must be considered in planning and design of capital and maintenance programs. Further, accurately monitoring asset performance in response to these factors enables more effective asset management.

The use of IHM (Infrastructure Health Monitoring) systems can assist owners in monitoring and managing the specific climatic impacts on transportation assets and can aid in developing asset management and maintenance strategies accordingly. Armed with real time and historic data on climate trends and related asset performance in a region, owners can prepare for the climate changes expected to come.

IHM, including structural health monitoring "IHM" for bridges and structures, is a mature concept and technologies such as those used in IHM have been in existence for decades. These systems have been developed to include a wide variety of features specific to the needs of the owner. They can remotely monitor and report in-situ stresses, strains, vehicle loads, vehicle dimensions, surface and air temperatures and other data.

A number of IHM systems have been designed for structures in Manitoba dating back to the late 1990's. Wardrop Engineering Inc. was involved in a number of these and was recently engaged by the Manitoba Floodway Authority (MFA) to design and implement a 46 sensor IHM system for the new floodway crossing on the TransCanada Highway (TCH1E) east of Winnipeg.

The IHM system for the TCH1E bridge aims to provide continuous feedback for the structural performance of the bridge. This will assist Manitoba Infrastructure and Transportation with its overall bridge management/maintenance plan as it assumes ownership of the assets from MFA. Sensors were installed on the bridge girders and deck. The sensors will measure strain, vibration characteristics, deformation and temperature data. The data are stored on dedicated server and can be accessed through a web page currently hosted by Wardrop (http://tch1.wardrop.net).

This paper introduces the merits of IHM systems, their applicability to monitoring impacts of climate change on transportation infrastructure and discusses the recent MFA IHM case study in Manitoba.

Key Words: climate change, infrastructure health monitoring, structural health monitoring

Introduction

Climate change is defined as any long-term significant change in the “average weather” that a given region experiences. Also known as global warming, this trend of increase in the average temperature of the Earth’s near-surface air and oceans has escalated since the mid-twentieth century and is projected to continue. Strong evidence of this trend has been seen around the globe. As a northern country, Canada is expected to warm more than many other countries. Though this might give Canada longer growing seasons or perhaps less demand for heat energy in the winter, the country will most definitely experience negative impacts such as depletion of fresh water sources, rises in sea level, and melting permafrost.

Strong evidence shows that both minimum and maximum temperatures have been warming in most of Canada over the past 50 years and that change in temperature distribution is expected to continue throughout the present century. In general, an increase in the frequency of extreme hot days in most regions of Canada and a decrease in the frequency of extreme cold days are expected. The associated impacts of climate change will vary regionally, reflecting differences both in the magnitude of climate changes and in environmental conditions.

Civil infrastructure systems are generally the most expensive assets in any country and are currently deteriorating at an alarming rate. An increase in the frequency and severity of hot days raises concerns that Canada's roads could experience further problems related to pavement softening and traffic-related rutting, as well as the migration of liquid asphalt (flushing and bleeding) to pavement surfaces from older or poorly constructed pavements. Asphalt rutting may become a greater problem during extended periods of summer heat on roads and bridges with heavy truck traffic, whereas some flushing could occur with older pavements and/or those with excess asphalt content.

Southern parts of Canada may experience fewer freeze-thaw cycles as a result of climate change, and thus may experience less frost damage to pavements. By contrast, in northern areas, pavement structures currently stay strong through the winter because the sub-grade remains frozen until spring. Milder winters with more freeze-thaw cycles could accelerate road deterioration and increase maintenance costs in northern areas. Degradation of permafrost as a result of climate warming will result in increased depth of the seasonal thaw layer, melting of any ice that occurs in that seasonal thaw zone, and warming of the frozen zone, which reduces its bearing capacity.

In Canada's North, melting permafrost will likely affect infrastructure and transportation, including the integrity of foundations (pipelines, bridges and buildings), water control structures, ice-roads and the melting of the assumed impermeable permafrost beds of mine-tailing ponds and landfill sites.

The use of Infrastructure Health Monitoring (IHM) may be able to assist in tracking and managing the effects of climate change. IHM is an evolving technology that can monitor and define the health of emerging or existing civil engineering infrastructure. IHM techniques originated in test laboratories and were used to examine the performance of structural samples. This technology has been introduced into the engineering practice over the past twenty years and is now used to augment the management of civil infrastructure systems by optimizing the operation, maintenance, repair and replacement of structures through the gathering and analysis of more reliable, consistent and objective data on their condition.

The implementation of IHM in response to the effects of climate change includes tasks aimed at evaluating, calibrating and applying several promising approaches for detecting small structural changes or anomalies and quantifying their effects all the way up to the infrastructure development decision making process with more accuracy and consistency than previously possible. Maximizing cost savings to taxpayers is the ultimate goal of IHM; in applying the technology in response to the effects of climate change, further such benefits may be realized.

Wardrop’s IHM Project Models

Wardrop has incorporated IHM technology into several projects including most notably the Taylor Bridge at Headingly, Manitoba, which was the first structure worldwide to be monitored remotely via a telecommunications line, the Esplanade Riel Pedestrian Bridge Project in Winnipeg, Manitoba, whose system provides some of the most complete IHM analyses of a cable-stayed structure in the world, and most recently, the Trans Canada Highway No. 1 East Twin Bridges, which stretch across the Manitoba Floodway.

Taylor Bridge, Headingly, Manitoba

The Taylor Bridge, the world’s longest span bridge using carbon fiber reinforced polymer, is located on Provincial Road No. 334 over the Assiniboine River in Headingly, Manitoba. The total length of the bridge is 165m; it is divided into five equal spans with each span consisting of eight 1.8m deep I-shaped precast prestressed concrete girders. Known as a “smart” structure, the Taylor Bridge is instrumented with fiber optic sensors coupled with conventional electric strain gauges embedded in the bridge girders, deck slab and barrier wall. Data are transmitted through two telephone lines fro continuous monitoring of the bridge under traffic loads and extreme environmental conditions. A camera also provides synchronized video information.

Esplanade Riel Pedestrian Bridge, Winnipeg, Manitoba

The Provencher Pedestrian Bridge is Winnipeg’s first cable supported structure. Performance of the bridge is continuously monitored and evaluated using IHM structural sensing technology. Wardrop designed the IHM system with a network consisting of various sensors and a central DAQ system. Several types of sensors are used, including eighteen fibre optic sensors, thirty electric strain gauges, thirty thermocouples, nineteen unidirectional and four tri-axial accelerometers, a wind monitor, fourteen electronic inclinometers and a web camera. The DAQ system resides in the west abutment and is connected to the Internet via a high-speed cable modem.

The cable-stayed pedestrian bridge is 5m wide and 200m long with a 57m high pylon in the middle. The bridge has two spans, the east span and the west span, which are 106m and 86m long respectively. The bridge also features a 370m^2 semicircular centre plaza around the main support pylon; this area is covered by a roof that is supported off the pylon and the surrounding ring beam. The bridge deck and pylon are made of reinforced concrete, while the stay cables are made of high strength steel strands. The cable-stayed structure, which features a large plaza at the pylon for commercial activities, has become a landmark in Winnipeg’s cityscape.

TransCanada Highway (TCH) No.1 East Bridge

The Trans Canada Highway No. 1 East Twin Bridges stretch across the Manitoba Floodway, which was originally constructed following the 1950 Manitoba flood. The Floodway is currently being expanded to accommodate a 1-in-700 year flood event, which requires changes to the 12 existing bridges that presently cross the Floodway. The new twin bridges use the second-generation Steel Free Deck (SFD) slab system, which is free of internal steel reinforcement, and contains nominal non-metallic and corrosion resistant Glass Fibre Reinforced Polymer (GFRP) bars. The deck slab is supported by Nebraska University (NU) pre-cast pre-stressed concrete girders, 2.0 m deep spanning 43.5 m. This is the first time NU pre-cast, pre-stressed concrete girders have been used in Manitoba.

To monitor the performance of the SFD system, an IHM system was installed on one of the twin bridges to diagnose the condition of the deck slab and ensure it was performing as planned. The SFD system makes the bridges less susceptible to corrosion and increases their load-carrying capacity, while the IHM system helps ensure that safety and integrity are not compromised.

The sensors that provide measurements of engineering data are located on or within the bridge superstructure. Wires leading from each of the sensors are located within electrical conduit and all lead wires are terminated within an electrical enclosure found in close proximity to the bridge site. Inside the electrical enclosure is the PC that processes the software required to operate the DAQ and an uninterrupted power source.

The DAQ is connected to the PC, which is connected to the internet via a wireless internet service provided to the enclosure. A data storage and web page server is located at Wardrop's Winnipeg office. Data from each of the sensors is logged to the bridge site DAQ and published where it awaits a subscription or call for data from the data storage server. Once the data server has requested the data from the bridge site DAQ, it is transferred to the data storage server via the Internet.

The bridge site PC and the data storage server are both equipped with a software called pcAnywhere, which allows Wardrop Engineers anywhere in the world to access data or modify the data acquisition program to meet their specific requirements. A web page user interface is located on the data storage and web server and allows anyone at any time anywhere in the world to access live data from the TCH No. 1 East Bridge via the Internet at http://tch1.wardrop.net .

Infrastructure Health Monitoring (IHM) Methodology

Design of an IHM System

An IHM project begins with the design of the IHM system including sensors, data acquisition (DAQ) and data servers. The project continues with the installation of all IHM components on the structure. The final task involves management of the data. The following sections provide a description of the IHM project at TCH 1 Bridge.

The intent of the IHM system for TCH 1 was to determine the structural responses to be monitored for the infrastructure. The design included the following steps:

1. Design the IHM equipment needed.
2. Identify desired data acquisition system and computer systems.
3. Determine communication modem and data transfer requirements.
4. Design the IHM Central Server at owner's headquarters.
5. Prepare IHM design drawings and standard specifications to include:
    - Conduits, location of sensors and sensors' installation detailing
    - Junction boxes, pull boxes and main control room
    - Electrical and power requirements

- Detailed Bill of Materials for the contractor to order all sensors, main and lead wires, data acquisition, and computers (on-site and server).

IHM Installation

The designers of the IHM system must co-ordinate with the contract administrator at the bridge site and provide assistance in project management for the following tasks, undertaken by the general contractor or his subcontractors:

1. Purchase the specified sensors, lead wires and accessories.
2. Prepare needed access and electric power for the installation of the sensors.
3. Install the conduits, junction boxes, and the main control room.
4. Pull the main wires from the junction boxes to the main control room.
5. Test the main wires from the main control room to the terminating junction box.
6. Install a high speed Internet Service Provider (ISP)

The IHM subcontractor must undertake the following tasks related to the supply and installation of the IHM system:

1. Install the sensors as per the design drawings
2. Verify and calibrate the sensors prior to connection to the main wires.
3. Connect sensors to the main wires
4. Verify and calibrate the sensors after connection to the main wires.
5. Set-up the data acquisition system, resident computer, and server.
6. Install the data acquisition system, resident computer, and server at a location designated by owner
7. Connect the sensors to the data acquisition system.
8. Test and verify the IHM system

Data Management

Management of the data stream recorded from the different sensors is completed according to the following tasks:

1. Implement an object-oriented program for data management and decision making
2. Establish two web sites for the infrastructure: a public web site and an engineering web site with controlled access
3. Commission and maintain the IHM system for the first year data mining process
4. Test and calibrate the data management protocols (data collection, decision making, and user interface)

IHM System Specifications

The Civionics and IHM system for the TransCanada Highway (TCH) No.1 East Bridge consists of several different components:

1. 47 sensors (e.g., Electronic strain gauge, thermocouple, accelerometer, and inclinometer)
2. National Instruments data acquisition system (DAQ)
3. Personal computer (operates software for DAQ)
4. Uninterrupted power source (UPS)
5. Communications system (e.g. Internet and wireless Internet)
6. Data storage and web page server
7. Any personal computer (located anywhere in the world)

Effect of Temperature Change on Strains inside Concrete Girders, Taylor Bridge

Figure 1 shows change of strain of a reinforcing bar inside a concrete girder on Taylor Bridge. The strains and temperature were recorded over a seven-day period in Winter 1998 and Summer 1999. The change in strain from summer was about 40 microstrain.

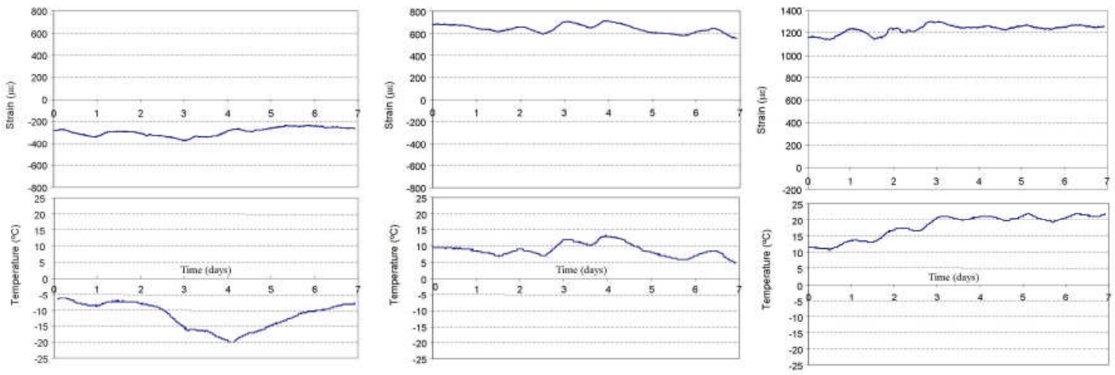

Figure 1 – Change of Strain of a Reinforcing Bar
Summer Versus Winter

Figure 2 shows the effect of a 36-ton truck on the same bridge to be less than 15 microstrain. Taylor Bridge is designed as simple spans free to expand and therefore temperature changes should not induce high stresses. However, continuous monitoring of strain versus temperature ensures that the bridge is responding to climate change in the intended way.

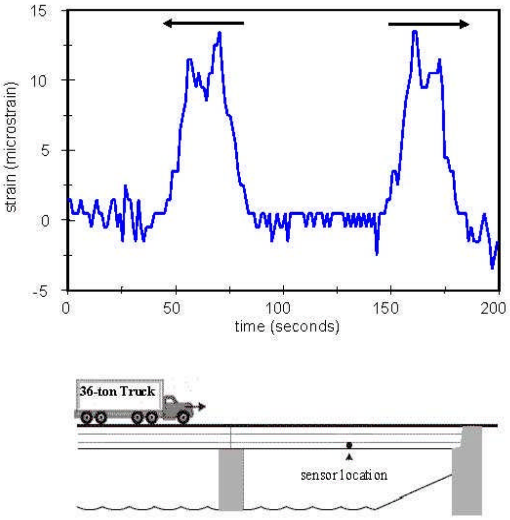

Figure 2 – Effect of 36-Ton Truck

The Objectives of Infrastructure Health Monitoring (IHM)

A bridge experiences far more change over its life span than a mere visual inspection can identify, change that may be further amplified by the effects of climatic warming trends. More like an organism than an object, a bridge's evolution depends on many uncertain events, both internal and external. Some uncertainties arise during construction, creating structural behavior that design and simulations can not predict. Once in use, each structure is subjected to evolving patterns of loads. Design can only predict so many different intensities and types of loads and in many cases they remain mostly unknown in both nature and magnitude. The sum of these uncertainties poses a great challenge to the engineers and institutions in charge of structural safety, maintenance and operation. They must define service levels and prioritize maintenance budgets amidst this uncertainty while relying only on models and superficial observation, which can lead to dangerous mistakes and inefficient use of resources. Regular inspection can reduce the level of uncertainty, but still presents significant limitations, namely restricting observation to short bursts spaced by long periods of inattention.

Infrastructure Health Monitoring (IHM) aims to provide more reliable data on the real condition of a structure by observing its evolution and detecting the early appearance of new degradations. By permanently installing a number of sensors and continuously measuring parameters relevant to the structural conditions, it is possible to obtain a real-time picture of the structure's state and evolution. In essence, it enables the bridge “organism” to detect its own sensitivities and tell you how it is performing under the loads it carries. It may even allow for better planning of inspection and maintenance activities by shifting the response from reactive interventions to on-demand assessment and failure prevention.

Infrastructure Health Monitoring (IHM) is designed to achieve the following:

- ***Reduce Uncertainty;*** More than ever before, those responsible for the well-being of a structure can know its true age, the real state of the materials and the real loads acting on the structure. Informed decisions supported by factual data create an environment for more successful maintenance.
- ***Allow Structural Management;*** Providing the ability to perform on-demand maintenance is one of the most significant objectives of IHM. Monitoring the evolution of a structure rather than reacting to its failures allows managers to optimize the operation, maintenance, repair and replacement of structures based on reliable and objective data.
- ***Discover Deficiencies Earlier;*** Some deficiencies appear in structures before they are detectable by visual inspection or modeling. IHM allows managers to complete repairs on these deficiencies sooner, at a lower cost and with less disruption to the structure’s use.
- ***Discover Hidden Structural Reserves;*** IHM allows you to characterize the true condition of a structure, thereby revealing areas that may be performing better than expected. This reduces the extra costs associated with over-design. Simply knowing that the bridge is in better shape than you thought allows you to extend its life and load-bearing capacity at lower cost.
- ***Increase Safety;*** IHM and the permanent, reliable data it provides allows a significantly higher level of safety for its users.
- ***Increase Knowledge;*** Knowing how a structure performs under real conditions allows an engineer to design better structures in the future. The monitored bridge is a structure that can tell you what to continue doing and what to do differently next time.

A Realistic Look at IHM’s Ability to Detect the Effects of Climate Change on Infrastructure

From 10,000 feet up, the notion of using IHM to detect the compounding effects of climatic warming on infrastructure makes perfect sense. We are already further than we’ve ever been in measuring a structure’s load allowances and distinguishing temperature, load and environmentally-induced stresses. Realistically, however, the idea of applying the science specifically to protecting infrastructure assets from the effects of climate change will need further study for several reasons:

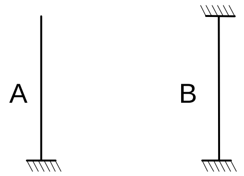

Figure 3 – Two bars with different restraints

- ***Temperature-induced strains are often interpreted incorrectly (Bakht 2004)***; to understand this problem, consider the two bars in Figure 3. Bar A is held against axial deformations at only one end, while Bar B is held rigidly at both ends. Subject both bars to a rise in temperature; Bar A will extend freely and experience no stress from the change in temperature. Bar B will not extend but will experience compressive stress. If both Bars A and B were installed with a strain gauge, the gross readings from the gauges would lead to false conclusions about the stress on the bars.

  Using a 'dummy' gauge installed on an unrestrained piece of the same materials as that of the instrumented component and using both gauges to form adjacent arms of the Wheatstone circuit (net strain in the component is the difference between readings from the active and dummy gauges), can be used to correct the measured strain readings. This simple and proven method, however, is not always used.

- ***The presence of stresses due to temperature is not always detrimental (Bakht, 2004);*** in statically determinate structures, all components are free to expand and contract, thus experiencing no stress due to changes in temperature.

- ***Not all structures change their pattern of load response with temperature;*** a structure's sensitivity to temperature is dependent on its design and several other factors. Some structures experience either none or such small temperature-induced forces they have practically no effect on the failure load of the structure.

- ***The science of IHM still suffers from a knowledge gap in data interpretation;*** while a lot of effort is being expended on the development of new sensors and the formulation of a philosophy for field application of IHM, little is being done on the interpretation of data. Current and future behavior of an instrumented structure, particularly as it relates to the increased fluctuations in temperature due to climate change, can only be determined based on an informed interpretation of the long-term data collected.

- ***Common terminology and metrics for monitoring infrastructures do not yet exist;*** we can not yet properly simulate infrastructure computer systems analytically, nor do we have a uniform system of measuring infrastructure performance. Before we can formulate meaningful metrics for life cycle cost and performance of infrastructure systems, we must learn how to evaluate the health actual operating infrastructures. Since IHM has only been introduced to civil engineering in the last 20 years, these capabilities are in their infancy.

The transportation infrastructure "organism" is subject to the same serendipities as the living, breathing carbon kind. Though not one of us is quite the same as the next, MRI's, CT Scans and ultrasounds wait on us organic anomalies, ready to make sure we're holding up just right, the same way IHM systems watch our structures for early detection of ailments. We can hope that the advances in managing infrastructure will allow us to extend the life cycle of a transportation system the way advances in medicine have extended our own. Evidence certainly shows that after emergency situations such as earthquakes, floods or hurricanes, data from these systems have saved many structures. It is the day to day monitoring, the more gradual changes that remain in question, particularly for emerging worries like climate change.

Similar to how IHM contributes to more accurate life cycle costing (LCC), LCC may serve to measure the benefits of IHM, but only if the LCC method adequately addresses real-world challenges like climate change. Research seems to agree that for the two to synergize, the LCC method must adapt to the uniqueness of infrastructures and respond to the inevitable uncertainties. It must consider uncertain and complex elements inherent in the evaluation of old structures in particular. It must also support an efficient process of engineering design and asset management efforts.

Civil designers and asset managers seem to agree on the following LCC method;

- ***Root method;*** the root LCC method requires simply the evaluation of customer needs, the review of technically feasible options, the development of cost estimates and profiles, equivalence measures, ranking of options and selection of the preferred option. These are deterministic analyses at their simplest.
- ***Sensitivity analysis;*** sensitivity analysis involves disturbing deterministic model variables over predetermined limits to determine their relative effect on LCC model outcome. This allows analysts to identify the variables exerting greater influence on model results. It is the first step in acknowledging the uncertainty that haunts deterministic analyses and begins to address the uniqueness of the infrastructure "organism."
- ***Risk analysis;*** the drawbacks of sensitivity analysis, namely failing to identify the dominant alternative, the inability to consider combined, simultaneous influence of several "disturbed" model variables, and the absence of probabilities, are addressed by risk analysis. Here we replace our uncertainties with probabilities.
- ***Iterative approach;*** depending on the value of information received through the feedback process, incorporating IHM feedback into the LCC process and making it iterative allow the LCC to continually improve upon itself. Feedback from previous iterations informs each stage of the design process to successfully refine the feasible design options and associated implications and costs. Here the issue of complexity is managed, if not overcome.

This method represents a broadly applicable way to develop LCC that is widely accepted for the management of complex civil infrastructure systems, particularly those monitored using IHM. In embracing a promising technology such as IHM for monitoring the effects of climate change on civil infrastructure, this LCC method allows asset managers to employ deterministic analysis, then measure the analyses' sensitivities, temper the exaggerations with probabilities, and finally, continually improve the process.

Conclusion

Realistically, IHM's ability to detect the effects of climate change on the transportation infrastructure "organism" has its challenges. No two systems are exactly alike, leaving transportation asset managers with decreased ability to standardize processes in their use of IHM. Temperature-induced strains detected on structures by IHM are often misinterpreted. Furthermore, the presence of stresses due to thermal forces is also not always detrimental and not all structures change their pattern of load response with temperature fluctuations. Finally the science of IHM still suffers from a knowledge gap in the interpretation of data the systems provide.

Like IHM technology, life cycle costing (LCC) of civil infrastructure is evolving. For the two to synergize, IHM must provide properly interpreted data and LCC must certainly adapt to the uniqueness of individual infrastructures, considering uncertain and complex elements and supporting an efficient, iterative process of engineering design and asset management efforts by incorporating sensitivity and risk analyses.

The implementation of this technology for this purpose will depend on:

- Adaptability of IHM systems to the specific needs of the civil infrastructures they monitor;
- Improved data interpretation;
- Correct isolation and interpretation of temperature-induced strain on IHM-monitored structures;
- Differentiating those structures affected by climatic warming from those that are not;
- Synergizing life cycle costing (LCC) and infrastructure health monitoring (IHM); and
- Developing adaptable approaches to detecting small structural changes or anomalies and quantifying their effects all the way up to the infrastructure development decision-making process with ever more accuracy and consistency.

Amidst other emerging technologies for managing infrastructure assets, we would characterize the use of IHM to monitor and respond to the warming effects of climate change on civil infrastructures, promising. Analysis of the IHM data can contribute to the development of cost-effective maintenance procedures that will save taxpayer dollars over time. Computer-based, automated signal-analysis algorithms will come to routinely process the incoming data and determine the feared anomalies based on pre-defined response thresholds. Upon authentication, appropriate action may be authorized for maintenance, early warning, and/or emergency response. Early access to information about the physical and structural state of the infrastructure will help identify potential risks.

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