INTRODUCTION OF NON-DESTRUCTIVE HIGHWAY INSPECTION METHODS USING HIGH DEFINITION VIDEO AND INFRARED TECHNOLOGY

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ABSTRACT

In these days of severe budget restrictions for many highway agencies worldwide, it has become increasingly difficult for highway department managers and engineers to respond to the ever increasing maintenance and rehabilitation demands of their deteriorating highway structures. In order to make timely and appropriate maintenance and rehabilitation decisions, constant monitoring of structural conditions is necessary. While most agencies recognize the importance of timely bridge inspections such programs tend to be time consuming and expensive.

In Japan, bridge owners face this dilemma of recognizing the critical importance of timely structure inspections while concurrently facing budget pressures brought on in part by the high labor costs and time requirements of their traditional visually oriented bridge inspection programs. To address this problem, Japanese engineers have worked to develop more efficient, economical and safer bridge inspection methods and procedures

Under these circumstances, one of Japan's major toll road operators (NEXCO-West) has been able to reduce highway structure inspection costs by developing and introducing an innovative highway inspection technical approach that uses a combination of high definition video (HDV) and infrared (IR) thermographic technology. High definition video records the surface condition of concrete structures. Recorded data is analyzed by image processing to determine crack widths and length on concrete surfaces Infrared imaging supports a thermographic assessment of structural integrity. In general, thermographic assessments involve analyzing structural integrity through an analysis of variations in a structural element's temperature at different times of the day; recognizing that damaged or deteriorating structural elements demonstrate different temperature variation gradients than do sound structural elements. Combining HDV and IR data enables an accurate assessment of a bridge's structural integrity.
This paper describes these inspection methods using HDV and infrared technologies and introduces some examples of practical on-site application to highway bridge superstructures. The technology can provide a powerful tool for engineers responsible for developing highway maintenance strategies and contribute to efficient and smart infrastructure management.

1. INTRODUCTION

Today, proper maintenance and management of deteriorating infrastructure under severe budget constraints have become serious issues for bridge owners. Traditionally, highway bridge conditions have been monitored by visual inspection with structural deficiencies being manually identified and classified by qualified engineers and inspectors. However, the quality of inspection results obtained through the traditional approach depends on the individual inspector's subjective judgment based on his/her knowledge and experience. In addition, these traditional inspection procedures require significant investments in both time and labour cost. These factors support the necessity for research and development for more reliable, objective and efficient bridge inspection methods.

With traditional site inspections, qualified inspectors are performing close-up visual inspections and sounding tests, often from crane suspended lifting cages or built-in inspection staging; arguably putting inspectors at some safety risk. The need for safer inspection methods calls for new innovations in bridge inspection technologies. In addition, new technologies that improve inspection efficiencies will help address the upcoming shortage of qualified bridge inspectors.

Bridge inspector responsibilities include preparing summaries of bridge condition factors that, by their nature, reflect the individual inspector's engineering judgement. If we can improve data collection efficiencies and reduce the time required by inspectors in the field to make general structure condition assessments, more time will be made available for these same inspectors to perform detailed hands-on inspection for those pre-screened bridge elements where structural defects require special attention.

The West Nippon Expressway Company Ltd. (NEXCO-West) has been working to develop efficient non-destructive highway bridge inspection methods using High Definition Video (HDV) and Infrared (IR) Imagery technologies. This paper describes the mechanisms of these inspection technologies and presents results from an on-site pilot project performed to evaluate the feasibility of these technologies in Florida, USA.

2. NEW INSPECTION TECHNOLOGY METHODS

2.1 INSPECTION METHODS USING HIGH DEFINITION VIDEO (HDV)

Recently, research and development on crack detection methodologies for efficient highway bridge inspection using digital images of the structures have seen significant technological progress. In the past, conventional inspection techniques using digital image processing had not been widely applied for practical use due to its limited image quality. The equipment was typically expensive and their application was limited primarily to technical research applications and special forensic professional services. However, recent innovations and improvements in image quality and data processing technology have contributed greatly to the technical viability of this inspection technology.

Figure 1 schematically shows the mechanism of pavement crack detection using HDV. The technology is the combination of GPS, GIS and HDV image pictures. The GPS navigation system, HDV and laptop computer are included inside the inspection vehicle. The HDV camera is attached on top of the inspection vehicle to record the surface condition (Figure 2).

The recorded data is analyzed by image processing to determine an individual structure's current condition as related to crack size, location and distribution. The detected cracks are identified in a digital crack map. The crack size and length are determined by computer software, and these quantitative characteristics are also summarized in spreadsheet format. The obtained crack maps and related data are provided to engineers for their subsequent structural diagnosis and rehabilitation planning.

A special advantage of HDV technology, with respect to crack identification and measurement, is the ease of maintaining a historical record of bridge cracks for use in monitoring crack propagation over time. The image processing includes a two- gradation analysis and line featuring analysis. The first step of the two-gradation analysis converts the digital picture into binary (black-and-white) data by analyzing the degree of colour transition from the nearby pixels, enabling our computer program to differentiate the spectrum and identify individual cracks. The second step then identifies the lines of black pixels in order to confirm the existence of cracks (see Figure 3).

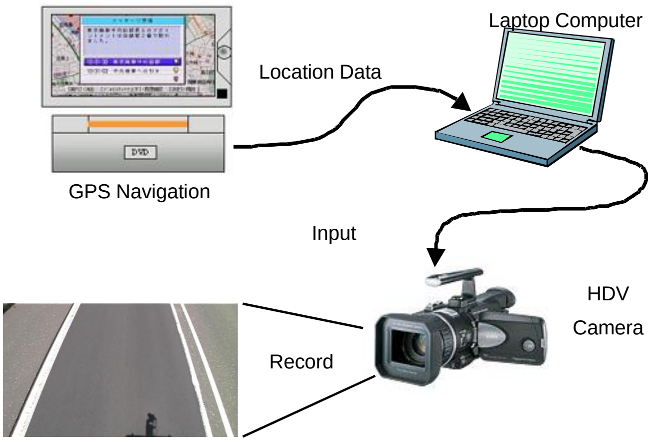


Figure 1 - Mechanism of HDV Recording for Asphalt Pavement Crack Detection

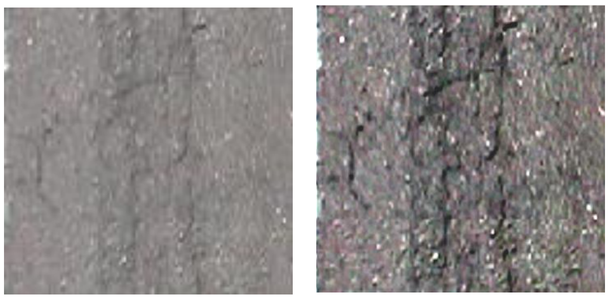


Figure 2 - HDV-Equipped Inspection Vehicle   Figure 3 - Mechanism of Image Processing

2.2 INSPECTION METHOD USING INFRARED (IR) IMAGERY TECHNOLOGY

Infrared imagery technology is a non-destructive testing method to locate possible delamination and spalling of concrete through the monitoring of temperature variations on a concrete surface using infrared thermography technology. IR technology offers inspectors the advantage of being able to identify likely delaminated, spalled and inner void areas from a distance of up to 5 meters with reasonable accuracy; thus avoiding the time and expense of gaining immediate access to the concrete surface to conduct traditional sounding tests. The results of IR images provide bridge owners a reliable screening of potential concrete defects on concrete structures that have been traditionally obtained by more time consuming (and probably more expensive) sounding tests. By applying IR technology to the concrete inspection process, inspectors can focus their hand-on sounding test activities on those areas shown through IR imaging as likely to be defective.

Figure 4 schematically shows the mechanism of infrared thermography method. The red line shows daily temperature variation for delaminated concrete, while the blue line shows the daily temperature variation for concrete in good condition. The delaminated concrete surface shows different temperature variation (see Figure 5). Infrared imagery technology is applicable during the periods when temperature differentials are detectable over time (IR imagery period A and B in Figure 4). It is not always possible to detect delamination of concrete only from the colour variation of infrared imagery since the concrete structure itself tends to have a temperature gradient depending on location and orientation with respect to the sun. Akashi et al. [1] performed the statistical and analytical study on the relationship between characteristics of temperature variation and inherent damage of the concrete, and developed an automatic damage classification system (J-System ®) that can classify the damage rate into three categories; the classification categories being "Critical" (crack exists on concrete surface and immediate attention is required), "Caution" (crack exists within 2cm from the concrete surface and close monitoring is recommended) and "Observation" (currently satisfactory) (see Figure 6). In Japan, spalling of concrete debris from expressway bridges has become a serious issue. In order to prevent hazards to the third parties, comprehensive sounding tests have been performed on all potentially hazardous concrete surfaces exposed to motorist and pedestrian traffic. Using IR thermography technology, engineers can check the delamination and/or spalling of concrete about three times faster than they can by conducting conventional sounding tests because IR technology applications require significantly less staging to secure adequate site access and correspondingly less traffic control to collect the required field data. Concurrently IR versus traditional sounding tests offer a 40% cost savings.

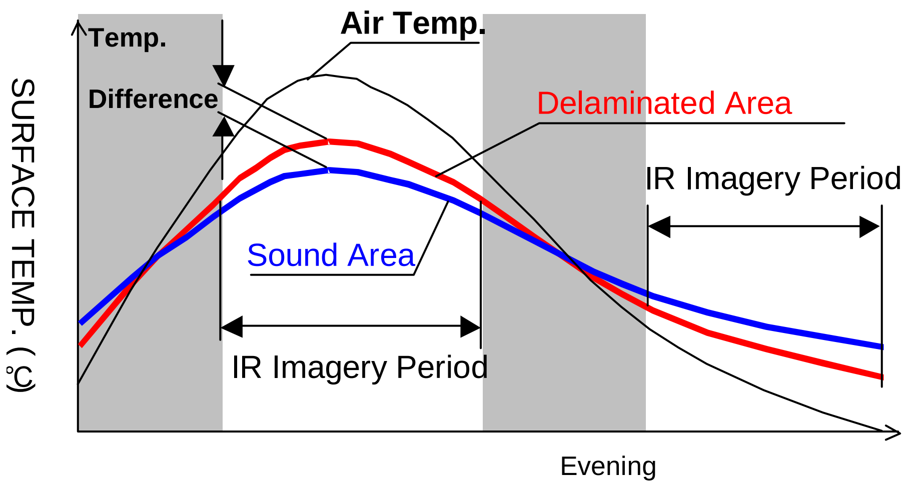


Figure 4 - Temperature Variation During the Day

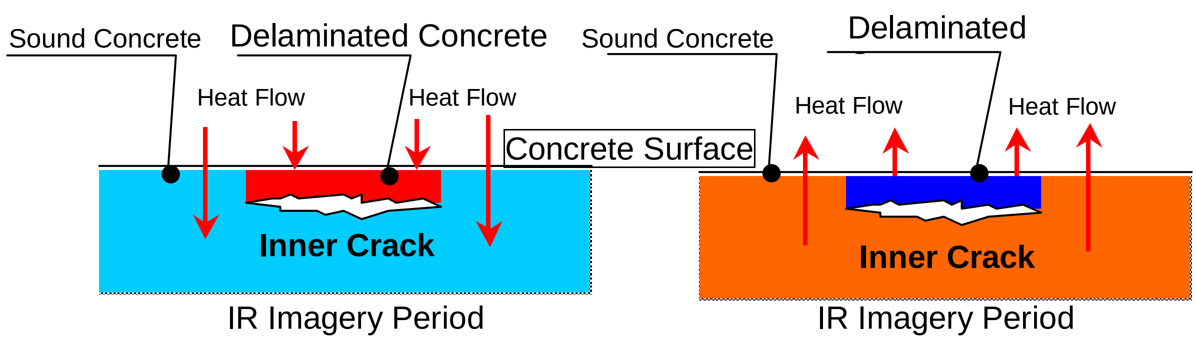


Figure 5 - Mechanism of Infrared Imagery Technology

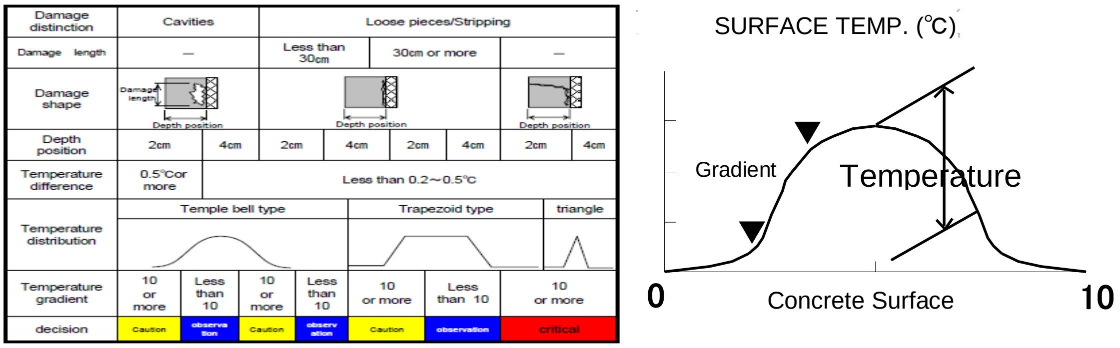


Figure 6 - Damage Rating by Infrared Imagery Technology

2.3 COMBINATION OF HDV AND IR IMAGERY TECHNOLOGY

HDV technology provides bridge inspectors visual digital information on concrete surface conditions that have traditionally been obtained from close-up visual inspections. Concurrently, the IR imagery technology corresponds to the sounding tests that traditionally have been used to detect voids, delaminations, and/or areas of spalled concrete (see Table 1). Most of the information from the visual inspection and the sounding tests can be obtained by a combined inspection using HDV and IR imagery technology. Effectively combining these technologies can contribute to reduced time for on-site inspection and inspection report preparation, allowing engineers to have more opportunities to devote themselves to the engineering issues such as structural diagnosis and strategic rehabilitation planning.

The advantages of applying new inspection technology include;
- Minimizing the human error factors (improve objectivity)
- Providing digital record for historical inspection data comparisons
- Improve efficiencies in bridge inspection resource application

Table 1 - Purpose of the New Inspection Technologies

	Purpose of Inspection	Traditional Approach
HDV	Surface Condition of the Structure (ex. Crack Map)	Visual Inspection
IR Imagery	Inner Void, Delamination and Spalling of Concrete	Sounding Test

3. THE ON-SITE PILOT PROJECT IN THE UNITED STATES

3.1 INTRODUCTION TO THE PILOT PROJECT

In order to validate effectiveness of the new inspection technologies, a pilot inspection project was conducted at the Seven Mile Bridge on US Route 1 in Florida Keys (see Figure 7). Currently, condition of the bridge is regularly monitored through established visual inspection procedures performed by qualified inspectors.

3.2 THE PILOT PROJECT RESULTS

(1) Deck Surface Inspection Using HDV

In order to record the deck surface cracks using an HDV camera, proper height (approximately 3 meters) and recording angle (no greater than 45° from vertical) are required. The HDV camera was attached to a custom-made camera mount and video data was gathered facing in the backward direction. HDV recordings of the concrete deck surface were conducted at a speed of 70km/h.

Figure 8 shows an example of a crack map for a concrete deck surface. Cracks of 3mm or greater were detected by a software supported automatic crack detection program, followed by supplemental manual crack checking by an experienced engineer. Manual crack checking successfully detected cracks of 0.8mm or greater. According to the Bridge Inspectors Field Guide [2], cracks should be classified into three categories as shown in Table 2, and the NBI (National Bridge Inventory) specified "Distressed Area" is calculated for the rectangular area including "Significant," "Moderate," or "Severe" cracks. Inspectors are responsible for proposing priorities on rehabilitation to the bridge owners by comparing the "Distressed Area" for each span or bridge. The results of pilot area bridge deck surface inspections proved the accuracy of crack detection using HDV technology to be satisfactory for routine in-service deck inspections. The new inspection technology provides additional benefits by increasing the level of safety for both inspectors and motorists and storing position recorded historical inspection data for monitoring of crack propagation. The digital crack map database can be a powerful tool for supporting those engineers responsible for maintenance plan preparation and work task priority decision-making.

Figure 7 - Location of the Seven Mile Bridge

Figure 8 - An Example of Crack Map for Concrete Deck Top

Table 2 - Categorization of Crack Size [2]

	Insignificant	Moderate	Severe
Crack Size	<1.6mm	1.6mm-6.3mm	>6.3mm

(2) Bridge Inspection using High Definition Video (HDV)
The underside of the bridge superstructure was photographed by HDV from a boat. Due to the boat's motion from wave action, the allowable recording range needs to be addressed by using three HDV cameras with a combined 1.56 million pixel image, a resolution that enables the user to include a 2-meter wide targeted object within a 3600 wide pixel image. This approach enabled identification of cracks in the 0.2mm to 0.5mm range through an analysis of the relative grey tone of the pixels denoting the cracks. The pilot project section consists of seven continuous spans of a post tensioned segmental box girder bridge. HDV photography involved seven separate passes of the boat beneath the bridge as shown in Figure 9 in order to capture all of the required HDV images.

The time required to record HDV images for the lower surface of all seven spans was about 2.5 hours. The recorded data obtained by the three cameras were combined automatically using proprietary computer software. By magnifying the digital image on the computer, existing cracks were visually detected by an experienced engineer trained to interpret HDV images.

To validate the results of the computer generated HDV crack detection assessment and to perform more detailed crack detection, an 'electronic crack gauge' is superimposed onto the HDV image. Engineers can manoeuvre the gauge on the HDV image and manually validate computer based crack width measurements. The detected cracks are categorized into three ranks (Rank 1: ≤0.5mm, Rank 2: >0.5mm to 0.7mm, Rank 3: 0.7mm or greater). The crack width, length and location data developed by using HDV applications can provide powerful decision making support information for engineers with bridge maintenance planning responsibilities.

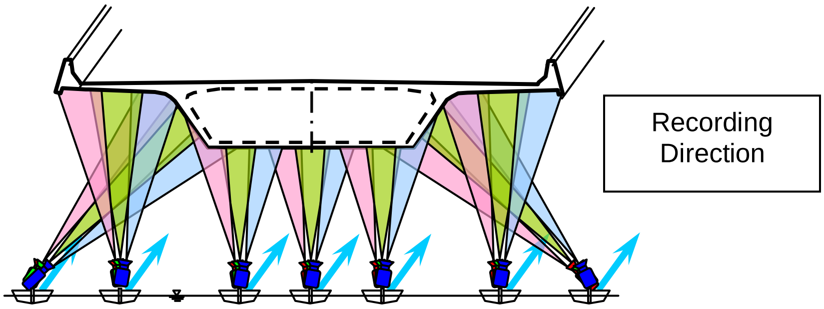


Figure 9 - Recording of Concrete Bridge Superstructure Surface by Three HDV Cameras

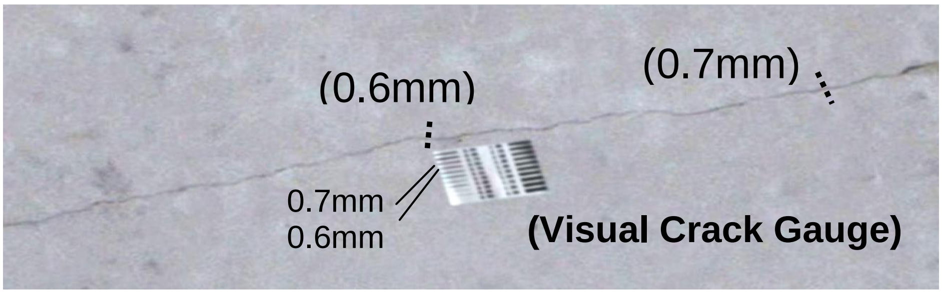


Figure 10 - Enlarged Image of Detected Cracks (Example)

(3) Bridge Inspection Using Infrared Imagery Technology
The infrared images of the pilot project section were photographed by a boat-mounted camera from underneath the bridge. The time required to photograph the entire lower bridge superstructure surfaces (soffit, exterior stems and deck overhangs) of the seven spans was about 2 hours.

Since the accuracy of damage identification using infrared imagery is greatly affected by daily temperature variation, accurate monitoring of the infrared (IR) photographing environment is mandatory. Figure 11 shows the equipment used for monitoring the temperature condition on the concrete surface. Three concrete test pieces with artificial flaws were attached to the bridge's underside surface. Taking infrared images of the concrete 'set-up' test pieces enabled the field infrared imaging team to see if there was sufficient temperature difference between damaged and non-damaged areas at any given time to permit further diagnostic IR imaging of the test area. Based on analysis of a 24 hour time-temperature record, it was concluded that the best available time period to apply infrared technology was from 9pm to 2am. During the photographing process, the infrared images of set-up test pieces were periodically checked in order to make sure that the field infrared imaging team was always in proper IR imaging environment. Figure 12 (a)(b)(c) shows an example of test results using IR imagery technology. The result of damage rating in Figure 12(c) shows three clusters of red spots indicating "Critical" condition. However, by checking the digital photo in Figure 12 (a), we can easily recognize that the spots at both sides are for drainage outlets. Using the output from the damage classification system, we can estimate the approximate spall area surrounded by red rectangle in Figure 12(c). Calculating the total spall area for each span or bridge provides engineers a quantified basis for prioritizing alternatives in a bridge structure rehabilitation plan.

Combining the results of HDV and IR imagery technology can produce synergetic effects that provide decision-makers with very useful structure condition information. By superimposing IR images, after specific location damage classifications have been made, onto the HDV image and resulting crack map of the same area, engineers can readily identify areas of likely structural damage, both on the surface and below the surface of the concrete.

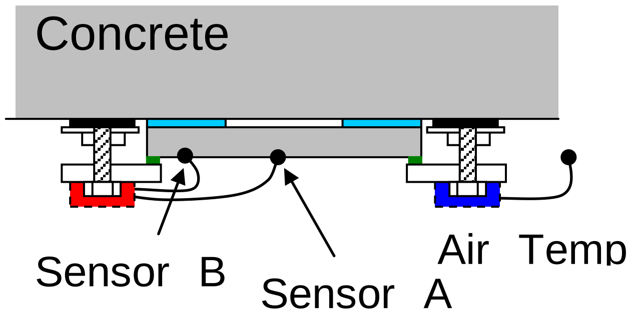
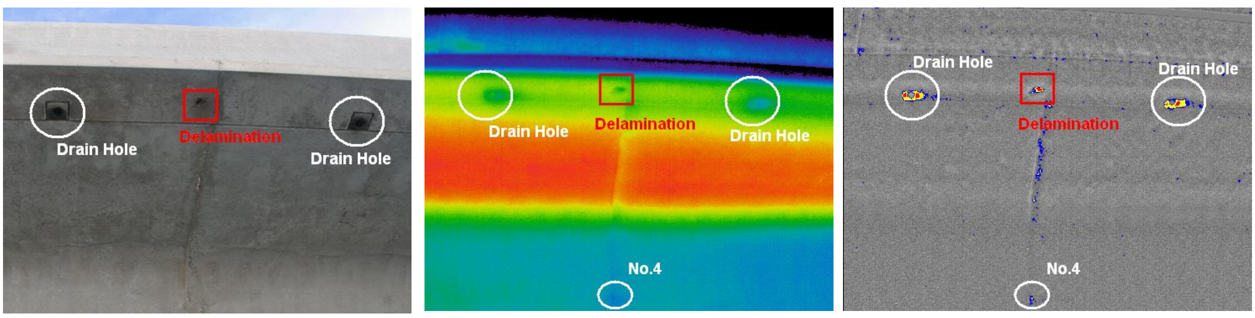


Figure 11 - The "Set-up Test Piece"



(a) Photograph (b) IR Imagery (c) Damage Rating

Figure 12 - Results of the Inspection using IR Imagery Technology

4. POTENTIAL APPLICATIONS OF HDV AND IR IMAGERY TECHNOLOGIES

HDV and IR imagery technology can be applied for both in-service bridge inspection and checking new structures for specification compliance (in terms of crack area percentage) at the time of construction acceptance. HDV technology has also been used successfully for supporting night time striping reflectivity tests. IR imagery technology has many other uses as well. Among applications relevant to maintenance and rehabilitation is the ability to use IR imaging to monitor areas of structural distress that have been covered with fibre reinforced polymer (FRP) materials. Another application is to identify subsurface irregularities (grout covered rock pockets) in new construction structure immediately after the removal of form work.

5. SUMMARY AND CONCLUSIONS

This paper described the mechanism of non-destructive bridge inspection methods using HDV and IR imagery technology and results of the on-site pilot project performed to evaluate the feasibility of applying these technologies for in service bridge inspection in the State of Florida, USA.

It was verified from the pilot project results that the accuracy of detection and measurement surface cracks and potential subsurface deterioration using these new technologies provided satisfactory and acceptable results for practical routine and special condition bridge inspections in compliance with recognized inspection practices. It was also demonstrated that new HDV and IR technologies could significantly reduce site inspection times and on-site inspection resource requirements.

With the quantity of roadway structure assets increasing annually, coupled with concurrent increasing rates of deterioration being experienced by many of the existing structures, bridge owners need to find new and creative ways to ensure the structural safety of their bridges while they all too often face problems of reduced budgets and dedicated bridge inspection resources.

Using the proposed new HDV and IR technologies, bridge engineers can quickly and efficiently obtain objective current bridge condition information that has traditionally been obtained by more time consuming and, in some instances, more subjective close-up visual inspections and sounding tests. The digital output of these HDV and IR inspection techniques improves on-site inspection safety and objectivity and contributes to improved inspector efficiency by reducing significantly the amount of on-site inspection time in the field. However, it must be noted that while HDV and IR technologies do offer new efficiencies to the bridge inspection process, they are not a substitute for inspectors conducting on-site specific follow-up and detailed structure investigations. While improved efficiencies in bridge inspection brought about by the application of HDV and IR technologies bring significant benefits to the overall bridge inspection process, they are not a substitute for the continued need for sound experienced engineering judgement.

Currently, costs of traditional and new inspection technologies are similar with new tech's lower field data collection costs being somewhat offset by additional costs for computer supported analysis. We expect with likely improvements in computer technology that these new inspection technologies will become increasingly cost effective.

The authors believe that by offering experienced bridge engineers and inspectors new improved inspection technologies, bridge inspection programs will be strengthened through improved inspection data, increased safety and more economical operations…bringing tangible benefits to bridge owners and the motoring public alike.

Acknowledgement
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