Economic Evaluation of Commercial Remote Sensors for Bridge Health Monitoring

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Abstract

The Michigan Tech Transportation Institute (MTTI) and Michigan Tech Research Institute (MTRI), in cooperation with the Center for Automotive Research (CAR) and the Michigan Department of Transportation (MDOT), have investigated the use of remote sensing technologies to assess and monitor the condition of bridge infrastructure. This study was funded largely by the USDOT Research and Innovative Technology Administration as part of an effort to improve the efficiency and cost-effectiveness of bridge inspection, repair, and rehabilitation efforts. Remote sensing technologies were correlated with in-place sensors and traditional inspection methods to obtain bridge condition assessment data and evaluate them as part of an integrated decision support environment to move them toward practical use in structural health monitoring. As part of the overall effort, CAR researchers conducted an evaluation of the cost-effectiveness of a broad deployment of remote sensing techniques for bridge condition assessment and a decision support system (DSS) for bridge infrastructure management. After background research, laboratory testing, field demonstration, and interviews with bridge inspection experts, three technologies emerged as having the most potential for cost-effective implementation: 3D Optical Bridge Evaluation System (3DOBS), Thermal Infrared Imagery (ThIR), and Ultra Wide Band Imaging RADAR System (UWBIRS). The researchers conclude that investment in remote sensing technologies for bridge health monitoring can enhance technical performance of bridge inspection and improve the resource allocation decision process for transportation agencies. Use of these technologies can be especially beneficial when combined with a decision support system (DSS), such as that developed by the research team.

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INTRODUCTION

Routine bridge inspections are an essential component of the decision making process for resource allocation for transportation agencies, but the inspections themselves also require a significant amount of labor and other resources. For most bridges, the National Bridge Inspection Standards (NBIS) suggests a 24-month interval for routine inspections. Routine inspection is described as "regularly scheduled inspection consisting of observations and/or measurements needed to determine the physical and functional condition of the bridge, to identify any changes from initial or previously recorded conditions, and to ensure that the structure continues to satisfy present service requirements" (TRB, 2007).

To assess the potential for remote sensing technology to improve the bridge monitoring and inspection process—that is, to make it higher quality, less expensive, or both—the Michigan Tech Transportation Institute (MTTI) and Michigan Tech Research Institute (MTRI), in cooperation with the Center for Automotive Research (CAR) and the Michigan Department of Transportation (MDOT), have investigated the use of remote sensing technologies to assess and monitor the condition of bridge infrastructure. The research was conducted as part of efforts by the USDOT Research and Innovative Technology Administration to improve the efficiency of bridge inspection, repair, and rehabilitation efforts. Most of the effort consisted of correlating the outputs of remote sensing technologies with those from in-place sensors and traditional inspection methods to obtain bridge condition assessment data and evaluate them as part of an integrated decision support environment to move them towards practical use in structural health monitoring. In addition to these technical efforts, CAR evaluated the cost-effectiveness of a broad deployment of remote sensing techniques for bridge condition assessment and a decision support system (DSS) for bridge infrastructure management.

The research team deployed and tested eight remote sensing technologies:

1. 3D Optical Bridge-evaluation System (3DOBS)
2. BridgeViewer Remote Camera System (BVRCS)
3. GigaPan StreetView-style Photography
4. Thermal Infrared Imagery (ThIR)
5. Digital Image Correlation (DIC)
6. Light Detection and Ranging (LiDAR)
7. Ultra Wide Band Imaging RADAR System (UWBIRS) (a form of Ground Penetrating Radar (GPR))
8. Synthetic Aperture Radar (SAR)

EXISTING BRIDGE INSPECTION PRACTICES

Currently most inspections are visual based, though non-destructive evaluation (NDE) methods are becoming popular in augmenting the visual inspections and subsequent evaluations advocated. Michigan conducts routine inspections on bridges every 24 months per federal requirements. After routine inspections, about five to seven percent of bridges are selected for in-depth "scoping" inspections, which require traffic closure. Traditional NDE structural health monitoring techniques include:

- Strain gauges
- Deflectometers
- Accelerometers

- Live load vehicles
- Hammer-sounding
- Chain-dragging
- Photographs

Cost Estimates for Current Bridge Inspection Techniques

Estimating bridge inspection costs is complicated because the data are not readily available in most cases. Agency experience or budgets are the only practical source for cost estimates. Most DOTs include regularly scheduled inspections costs in their "normal" or "preventive" maintenance budget because bridge inspection is often part of a DOT's overall highway maintenance, repair, and traffic operations program (TRB, 2003). This study collected data through a literature review and face-to-face interviews with MDOT partners to establish realistic agency cost estimates of current bridge inspections.

Bridge inspection and management experts report that the primary component of bridge inspection costs is the cost of labor. For most routine inspections, a team of two can complete four to five bridges per day. Large or complex bridges may take longer. Thus, the cost of a routine inspection can be highly variable, based on factors such as size, location, traffic volume, and construction type. Non-routine inspections (e.g., in-depth, fracture critical) may also cost more. Historical bridge inspection cost data from CAR research is summarized in Table 1.

Table 1: Sample of Bridge Inspection Costs for Selected Transportation Agencies

State/County/City	Bridge Inspection Cost	# of Bridges Inspected Annually	Period	Annual Inspection Cost Per Bridge	Type of Inspection Services
Michigan (1)	$2.0 million	2,000	FY2010	$900	In-house plus contract
Wisconsin (2)	$2.32 million	2,542	FY 2006-07	$917	$1.01M for contractors; $1.31M for in-house
Armstrong County, Pennsylvania (3)	$482,172	34	2010 to 2015	$2,398	Contract service with PennDOT
Tulsa County, Oklahoma (4)	$70,000	195	2007 - 2008	$359	Contract service
Coal County, Oklahoma (4)	$18,300	52	2009 - 2010	$352	Contract service
Logan County, Oklahoma (4)	$88,000	231	2007 - 2008	$381	Contract service
Oklahoma Turnpike (4)	$150,000	399	Since 1998	$376	Contract service
Tulsa District (4)	$84,100	12 Spillway bridges	2003	$7,008	Contract service
Tulsa District (4)	$109,700	7 Spillway bridges	2004	$15,671	Contract service

Sources: (1) Interviews with MDOT Bridge Inspection Team; (2) Wisconsin Legislative Audit Bureau (2008); (3) TribLive News (2010); (4) Oklahoma Department of Transportation (2010).

Bridge Scoping

Scoping is a more rigorous bridge inspection process conducted when it has been determined that a bridge is in need of rehabilitation. The purpose of bridge scoping is to evaluate a bridge for various repair alternatives, recommend the most economical rehabilitation or treatment, and develop a scope of work and cost estimate for the selected alternative. The work for each bridge scoping includes two major steps: site review and engineering analysis. According to MDOT, about 167 state-owned bridges were scoped in 2010 at an average cost of $9,329 per bridge. This cost is not included in the routine inspection costs given in Table 1.

REMOTE SENSING TECHNOLOGIES FOR BRIDGE CONDITION ASSESSMENT

Three Michigan DOT bridges were selected for field demonstration of using commercially available remote sensing technologies to enhance bridge inspection. The bridges provide a range of condition ratings (from poor to good) and are the same construction type (pre-stressed concrete I-beam with concrete deck). The selection of bridges was intended to provide comparability between remote sensing results under a range of condition ratings. Eight remote sensing technologies were deployed, and each is summarized below. The benefits and limitations of each technology are summarized in Table 2.

3D Optical Bridge-evaluation System (3DOBS)

3DOBS uses a standard digital single lens reflex (SLR) camera and commercially available 3D close-range photogrammetric software to create a 3D model of the bridge deck surface. The 3D model then allows for objective quantification of surface defects such as percentage spalled, crack density, and surface roughness in the International Roughness Index (IRI) scale. The research team at MTRI developed automated algorithms for this purpose, using Python within ESRI ArcGIS. 3DOBS was investigated for defect detection on the underside of bridges in addition to the deck, but low-lighting conditions proved a challenge. Interviews with bridge inspection experts suggested that 3DOBS's capability of collecting quantifiable data at highway speed could be very valuable. 3DOBS was one of three technologies chosen for the detailed economic evaluation.

Bridge Viewer Remote Camera System (BVRCS)

BVRCS was developed for this study as a low-cost street-view photography data collection tool. The two-camera system is designed to capture a high-resolution image of a lane-width of bridge deck surface at near-highway speed. The images are instantaneously location-tagged with GPS to produce a geo-coded photo inventory of the bridge deck surface.

GigaPan Photography

The GigaPan system uses a robotic arm to collect high-resolution geo-tagged photographs that can be stitched into a single 360 degree image. GigaPan hardware and software is commercially available. GigaPan is intended to create a visual model and image database of the entire structure. Although the image files created by high resolution photography can be quite large, GigaPan offers free data storage for images captured by the system. GigaPan technology could be deployed periodically to remotely monitor changes over time, or verify results from other remote technologies such as 3DOBS and ThIR. When combined with data analysis software, GigaPan imagery may be able to monitor changes in crack density,

percent of spall areas, or other deterioration indicators that benefit from early detection and preventative maintenance. Data collection time can be extensive, and GigaPan hardware cannot be operated from a moving vehicle.

Thermal Infrared Imagery (ThIR)

A thermal infrared (ThIR) camera creates an image of variations in surface temperature of an object. Variations in surface temperature can reflect subsurface conditions. The benefit of this technology is that it can detect subsurface defects and anomalies that are not detected by visible-spectrum imaging methods. Subsurface defects, such as delaminations, are traditionally detected through time consuming and subjective methods such as chain dragging and hammer sounding.

A challenge in use of ThIR technology is that readings are highly variable depending on weather conditions and time of day. Also, there are various conditions that could result in a non-uniform thermal image that are not true flaws or deficiencies. Due to the variability of thermal images, there is not yet a standardized algorithm to objectively measure delaminations from ThIR readings. Thus ground-truth information should be employed by other methods to verify the results of the ThIR survey.

Interviews with bridge inspection experts indicated that even if data could not be automatically quantified, the ability to collect images that reflect subsurface conditions at highway speed would be very valuable. The research team has determined that ThIR technology for remote bridge evaluation is near user-ready. ThIR was selected as one of the three technologies chosen for detailed economic evaluation.

Digital Image Correlation (DIC)

DIC is a method of detecting changes in global bridge metrics such as settlement, vibration, and deformations. The technology works by correlating pixels on optical images to detect variations between time instances. Using a standard SLR camera and commercially available software, DIC can track movement and deformations under loading to model strain fields. DIC is a proven tool in laboratory research. However, the research team has concluded through field demonstrations that DIC technology may be difficult to implement as a real-world bridge inspection method—particularly because the camera must be extremely stable between takes.

Mobile Light Detection and Ranging (M-LiDAR)

LiDAR measures the properties of reflected light to generate a surface model of an object. LiDAR typically operates in the infrared or near-infrared range of the spectrum. This is intended to obviate the problem of distortion created by varying lighting conditions in the visible spectrum. Mobile LiDAR (M-LiDAR) systems are typically capable of operating at near highway speeds. A Mobile LIDAR System generally includes two to four scanners, cameras, antennae, positioning system including high-accuracy GPS and inertial navigation, and data processing software.

Synthetic Aperture Radar

Applications of Synthetic Aperture Radar (SAR) were investigated for utility for bridge condition assessment. In particular, the assessment of bridge settlement and overall bridge deck condition were thought to be areas that SAR data could be used effectively, based on recent studies and applications. SAR images are coherent radar images in three dimensions, where the first two coordinates specify the spatial location of a signal and the third coordinate contains the phase. It is the phase information from

which height or depth measurements are made. The SAR bridge settlement and road roughness measurements did not produce clear results.

Ultra Wide Band Imaging RADAR System (UWBIRS)

Interior features of bridge decks (i.e., delaminations, defects, and rebar) can be investigated with commercially available ground penetrating radar (GPR) systems. However, current methods generally require extended lane closures. This study investigated the potential for a radar system that could be deployed with minimal traffic disruption. The research team developed a field portable ultrawideband imaging radar system (UWBIRS) using commercially available components that are lower cost than traditional GPR technologies. The concept of operations is a system capable of subsurface characterization of bridge decks and components with minimal traffic disruption. The research team investigated use of UWBIRS to characterize concrete bridge decks and the internal structure of a salvaged box beam.

The UWBIRS results were found not to correlate to more accepted methods of subsurface investigation for the concrete bridge decks. Thus, the system as deployed is not considered commercially viable at this point. However, it is believed that the technology could be capable of reliable and detailed subsurface characterization with further testing and refinement of the algorithms used by the imaging software. Interviews with bridge inspection experts indicate that UWBIRS potential to detect the depth of subsurface defects, such as subsurface spalling, could be very valuable. For these reasons, UWBIRS was selected as one of the three technologies chosen for detailed economic evaluation.

Table 2: Benefits and Limitations of Remote Sensing Technologies for Bridge Assessment

Technology	Benefits	Current Limitations
3DOBS	• Low capital cost • Rapid deployment • Useful metrics (percent area and volume, and location of spalls) • International Roughness Index (IRI)	• Speed of collection (<5 MPH) • Traffic disruption • 5mm resolvable features (with current deployment; capable of higher-resolution)
BVRCS and GigaPan	• Low capital cost • Rapid deployment • Useful metrics (easily viewable geo-tagged photo inventory, can compare condition over time with multiple inventories)	• Automation of analysis • Not yet at highway speed • GigaPan storage
Thermal IR	• Useful metrics (percent delamination, detects subsurface defects) • Qualitative and quantitative assessment tool	• Collection time • Traffic disruption • Camera specifics • Data processing time and user interpretation
SAR	• Bridge settlement from satellite imagery • Road and bridge roughness of multiple bridges	• Need satellite image pairs before and after settlement • Need good geometry for SAR imagery to see road roughness
UWBIRS	• Potential for useful metrics (e.g., percent spall and delamination) • Detects surface and subsurface defects • Similar commercial 3-D systems are becoming available	• Not yet a commercially viable technology as deployed • Speed of collection (<5 mph)
DIC	• Can track changes in mechanical behavior over time • Useful metrics: remotely captures deflection, strain field and vibration (global system metric)	• Environmental effects: error induced by wind and traffic flow, more ideally suited in current form for controlled environments • Deployment time and cost
LiDAR	• Potential for useful metrics: percent spall and delamination • Detects surface	• High capital cost • Speed of deployment • Appropriate integration in bridge condition assessment framework

ECONOMIC EVALUATION METHODS

There are many types of full economic evaluation techniques, including cost-utility analysis (CUA), cost-effectiveness analysis (CEA), cost-minimization analysis (CMA), cost-benefit analysis (CBA) and cost-consequence analysis (CCA). However, these formal techniques were found to be insufficient for analysis of remote sensing technologies for bridge inspections. The incompatibility is due to the novelty of the

technologies and the cutting-edge nature of the research. To address these challenges, this research relied on technical assessments, interviews with MDOT stakeholders, previous research findings, and field cost calculation. During the analysis process, the factors explored below will influence final evaluation approaches.

Time Period of Analysis

The time period for an economic evaluation should maximize the anticipated economic efficiency of the alternatives. The timeframe to calculate total costs and benefits was mainly determined by the anticipated service life (in years) of major equipment. In this study, three different time-period options were considered: five years, ten years, and fifteen years. The primary difference is the payback period (and thus number of uses) over which the initial capital investment is assumed to be applied. The five year service life may be the preferred time period of analysis due to the rapid advancement of technologies and costs associated with technical support and upgrade.

Geographic Scope of the Analysis

The area included in the analysis is the State of Michigan, which has 4,397 state-owned NBI-length bridges in 2011. The extension of the geographic scope to a regional level (i.e., Michigan, Illinois, Ohio, Indiana, and Wisconsin) was also considered. However, it was determined that Michigan is of sufficient size to take advantage of economies of scale. It is estimated that MDOT could implement remote sensing technology on nearly all (98 percent) state-owned NBI-length bridges with three dedicated inspection units, assuming a 24-month inspection schedule.

Scale of Implementation

The scale of implementation reflects the percent of state-owned bridges that will be inspected with remote sensing technologies. This is assumed to be dependent on the time period of analysis, reflecting the tendency for new technologies to follow an adoption curve. This analysis considered 20 percent, 60 percent, and 100 percent implementation for five, ten, and fifteen year time periods of analysis, respectively. Because routine inspections usually follow a 24-month schedule, the percent implementation implies that half as many bridges are inspected on an annual basis. For example, for the five-year time horizon, a 20 percent scale of implementation is assumed, meaning that remote sensing technology is deployed on ten percent of state-owned bridges in a single year.

Available Inspection Days

Because of the Midwest's typical weather conditions, it was assumed that bridge inspection can only be conducted for seven months of the year (April to October), which is typical of MDOT's inspection period. This is equivalent to a 30-week inspection season. It was further assumed that on average three days per week are available for field inspection (the rest days are for planning or limited by the weather condition). This translates into 90 inspection days a year. Based on interviews with bridge inspection experts, it is estimated that a single team would complete about eight bridge inspections per day (assuming that these bridges are normal size and with reasonable access). Thus, the maximum number of bridges inspected by a single team within a year is approximately 720.

Service Life (In Uses)

Estimating the service life (in number of uses) of a remote sensing inspection unit provides a simple cost estimation method that bypasses complex calculations involving the preceding factors. Determining the total cost of implementation of a remote sensing technology for a given assumed service life requires only adding the capital (investment) costs and the total operational (per bridge) costs. Estimated per bridge costs then only requires dividing the total cost by the anticipated number of uses. This approach was necessary to compare per-bridge costs of purchasing and operating the technology in-house to contracting the service out without making assumptions about the time period of analysis. Because service life is time-independent, it is assumed in this case that an inspection vehicle is purchased at a cost of $30,000 in capital depreciation over the service life of the inspection unit—as opposed to a yearly leased rate as in more complex analysis.

QUANTIFYING COSTS OF REMOTE SENSING TECHNOLOGIES

Some cost elements are relatively straightforward and can be measured based on available market data and the field demonstration cost data collection efforts. Others, those with greater uncertainty, are not easily measured, such as final labor costs associated with inspection and data processing times. Careful analysis will need to be performed to estimate the cost of these technologies once at a commercially available stage, as research costs are not typically representative of implemented technology costs. Thus, the final cost database is being developed based on field demonstration cost data collection, interviews with vendors, and additional research. The summarized capital, operational, external, and service costs for all examined technologies are presented in Table 3. The items for which cost assumptions are stated include the following:

Data Collection System

The data collection system is assumed to include the major collection equipment, laptop, and software. No repair or maintenance costs were included. The cost of the system is estimated for the conceptual operational system as may be implemented by transportation agencies; this cost may vary widely from the cost of the equipment used by the research team for testing and field demonstration. Some system costs may vary significantly depending on the exact specifications and capabilities of the system. Additionally, rapidly decreasing technology costs may affect these costs in the near future.

Data Collection Vehicle

It is difficult to predict the data collection methods that will be implemented by transportation agencies. For example, existing fleet vehicles may be modified, or new vehicles may be purchased, or leased, for data collection. Additionally, the vehicles may be multi-use, or dedicated to remote sensing data collection. For the five, ten, and fifteen year scenarios, this analysis assumed a $9,600 per year vehicle cost, based on an $800 per month lease fee for a heavy-duty pickup truck. For service life (in uses) estimation (performed in order to compare the purchase and operate option to contracted service), it is assumed that a purchased vehicle will cost $30,000 in capital depreciation over the service life.

Data Storage and Backup

Data storage costs are difficult to predict for a future implementation time. Digital storage costs are decreasing. However, as some of these technologies generate significant amounts of data, the analysis

sought to account for this. Data storage and backup costs are estimated at $10 per GB per year. This price is based on the price of service from the Michigan Department of Technology, Management and Budget (DTMB), which provides full service network-attached storage that runs across a T1 for $9.60 per GB per year.

Labor (Data Collection and Processing)

Labor costs include the total costs of personnel to collect the data and extract the bridge condition information. Highway speed data collection is assumed to take 30 minutes per bridge. It was assumed that all technologies except GigaPan and DIC will be deployed at near highway speed. It was further assumed a two-person inspection crew was needed for all data collection. The data processing time ranges from one to sixteen hours per bridge. A uniform labor rate of $50 per hour was assumed. The analysis also assumes zero opportunity cost for underutilized labor. In other words, it is assumed that bridge inspectors are 100 percent utilized, regardless of work load.

External Costs (Lane and Shoulder Closures)

A major consideration in bridge inspection expenses is the external costs to road-users associated with traffic delays and lane closures. Calculations of road user costs require much location-specific information, such as length of highway affected by the activity, traffic speed during activity, normal traffic speed, annual average daily traffic (AADT), annual average daily truck traffic (AADTT), work zone crash rates, vehicle operating costs, etc.

Another example is the lane rental fee, which appears to be more appropriate for this study. Lane rental is commonly used in the roadway construction contracting process, meaning that the contractor has to pay for the time or right to use lanes during construction operations. This time component is converted to a cost to the contractor based on estimated road user costs, depending on, for example, whether one lane is occupied as opposed to a lane and a shoulder. In addition, rental rates can be different depending on the time of day (i.e., peak or off-peak travel hours). It was assumed that all technologies except GigaPan and DIC will be mounted on a vehicle and travel close to highway speed. SAR is primarily satellite-based and so is not further discussed in this context. As such, they will not generate any external costs. For the use of GigaPan, one shoulder closure is needed and the hourly fee is $125. For DIC, one shoulder and one lane closures are needed and the hourly fee is $625 (TRB 2000).

Service Fee (Contracted Service Option)

Transportation agencies frequently contract out current remote sensing data needs, such as high-resolution aerial photography collection, GPR and LiDAR data collection, from commercial services firms and may choose to do so for new remote sensing technologies as well. Contractors generally charge a set service fee per bridge for using certain types of technologies. Service costs are collected through interviews with vendors.

Table 3: Summary of Costs per Individual Technology

Cost Description	3DOBS	BVRCS	GigaPan	ThIR	DIC	M-LiDAR	UWBIRS
Data Collection Systems	$34,000	$7,000	$5,000	$30,000	$5,500	$500,000	$200,000
Data Collection Vehicle (Cost for one year)	$9,600	$9,600	$9,600	$9,600	$9,600	$9,600	$9,600
Size of Data Storage File (GB per bridge)	0.1	2.0	10.0	1.0	32.0	7.0	0.2
Data Storage Rate (per GB per year)	$10	$10	$10	$10	$10	$10	$10
Data Storage Cost (per year)*	$1.2	$20.0	$0.0	$10	$320	$70	$2
Data Collection Time (hours per bridge)	0.5	0.5	4	0.5	2.5	0.5	0.5
Personnel Needed for Data Collection	2	2	2	2	2	2	2
Total Data Collection Staff Hours	1	1	8	1	5	1	1
Data Processing Time (hours per bridge)	2	1	4	8	4	16	8
Total hours per bridge for all data collection and processing	3	2	12	9	9	17	9
Labor Rate (dollars per hour)	$50	$50	$50	$50	$50	$50	$50
Total Labor Cost (per bridge)	$150	$100	$600	$450	$450	$850	$450
Total per bridge Operational Costs (data storage and labor)	$151	$120	$600	$460	$770	$920	$452
Lane/Shoulder Closure Cost (dollars)	$0	$0	$600	$0	$1,563	$0	$0
	3DOBS	BVRCS	GigPan	ThIR	DIC	M-LiDAR	UWBIRS
Contractor's Charge per Bridge (Service Fee) (dollars)	$260	$260	$1,500	$1,300	$1,500	$1,800	$1,300

* GigaPan currently hosts the composite panorama images for its customers at no cost.

DEPLOYMENT OPTIONS AND COST ESTIMATES

Because each of the remote sensing technologies has its own advantages and disadvantages, combining technologies into a single remote bridge inspection unit multiplies the utility of a remote bridge inspection program. The technologies selected for further evaluation are: ThIR, 3DOBS, and UWBIRS. The selections were made based on technical evaluations and interviews with bridge inspection experts. As seen in Table 4, the combination of these three technologies allows for evaluation of 22 individual bridge performance measurements.

Table 4: Performance Measurements of Technologies Selected for further Economic Evaluation

	Challenges	Performance Measurement	ThIR	3DOBS	UWBIRS
Deck Surface	Expansion Joint	Torn/Missing Seal	✓	✓	
		Armored Plated Damage		✓	
		Cracks within 2 Feet		✓	
		Spalls within 2 Feet	✓	✓	
		Chemical Leaching on Bottom			
	Map Cracking	Surface Cracks		✓	
	Scaling	Depression in Surface	✓	✓	
	Spalling	Depression with Parallel Fracture	✓	✓	
	Delamination	Surface Cracks		✓	
Deck Subsurface	Expansion Joint	Material in Joint			
	Delamination	Moisture in Cracks	✓		✓
		Internal Horizontal Crack			
		Hollow Sound			
		Fracture Planes / Open Spaces	✓		✓
	Scaling	Depression in Surface (e.g. Interior of voided sections)			✓
	Spalling	Depression with Parallel Fracture (e.g. Interior of voided sections)			✓
	Corrosion	Corrosion Rate (Resistivity)			
	Rebar Corrosion	Change in Cross-Sectional Area			✓
	Chloride Ingress	Chloride Content through the Depth			✓
Girder Surface	Steel Structural Cracking	Surface Cracks			
	Concrete Structural Cracking	Surface Cracks	✓		
	Steel Section Loss	Change in Cross-Sectional Area			
	Paint	Paint Condition			
	Concrete Section Loss	Change in Cross-Sectional Area			
Girder Subsurface	Internal Concrete Structural Cracks	Internal Cracks (e.g. Box Beam)			✓
		Fracture Planes / Open Spaces	✓		✓
	Concrete Section Loss	Change in Cross-Sectional Area			
	Prestress Strand Breakage	Change in Cross-Sectional Area			✓
	Corrosion	Corrosion Rate (Resistivity)			
	Rebar Corrosion	Change in Cross-Sectional Area			✓
	Chloride Ingress	Chloride Content through the Depth			✓
Global Metrics	Bridge Length	Change in Bridge Length		✓	
	Bridge Settlement	Vertical Movement of Bridge			
	Bridge Movement	Transverse Directions			
	Surface Roughness	Surface Roughness		✓	
	Vibration or Live Load Deflection	Vibration or Live Load Deflection			

Selected "Packages"

The three technologies selected for further analysis were evaluated in a series of three service "packages." These packages are selected to optimize the marginal benefits for the marginal cost of implementation of each technology.

Basic Package

The basic package includes only thermal infrared (ThIR) imaging. Implementation of ThIR would provide a low-cost method of subsurface nondestructive evaluation. Use of this technology could negate the need for time-consuming and costly chain-drag and hammer-sounding methods of inspection for delamination.

Enhanced Package

The enhanced package includes ThIR and the 3D optical bridge evaluation system (3DOBS) developed by the research team. The combination of these technologies provides both surface and subsurface evaluations of bridge decks in a single system. 3D optic technology is an especially valuable tool because it is capable of automatically calculating global bridge health parameters such as percentage spall, crack density, and international roughness index (IRI).

Premium Package

The premium package includes ThIR, 3DOBS, and ultrawide band imaging radar system (UWBIRS) developed by the project team. The combination of these technologies provides both surface and subsurface evaluations of bridge decks in a single system. This package is not yet considered field ready, as further analysis and refinement is needed for calibration of the UWBIRS system. However, it is anticipated that when the UWBIRS system is developed, it will be capable of providing novel information about the condition of the subsurface of the bridge deck. UWBIRS may also be configured to evaluate other concrete bridge components such as box beams and walls.

Cost Analysis of Alternative Deployments

The measuring of costs associated with the three deployment options (basic, enhanced, and premium) are conducted in combination with other influencing factors (time period of analysis, geographic coverage, and service type). The measurements include annual total cost, average cost per bridge, and cost types. The highlights of these analytical results include:

- Annual average per bridge cost for using the basic service of Thermal IR ranges from $476 to $495 for the State of Michigan; the cost of adding 3DOBS or the enhanced service package will be about 23 percent higher ranging from $581 to $612 per bridge; The premium package (Thermal IR + 3DOBS + UWBIRS) costs between $1,001 and $1,105, about twice the basic service. The cost range is a function of the time period of analysis and scale of implementation (Table 5).

- Annual average cost per bridge using the "purchase and operate" service model is less than using contract services because of number of bridges in these calculations exceeded the balancing point, which ranges from 72 bridges for the basic service package to 155 bridges for the premium package (Figure 1).

- The selection of time period of analysis (5 years, 10 years, and 15 years) does not have a significant impact on annual average costs per bridge, mainly because the capital costs are small

proportion of the total costs. For example, the capital costs for the five-year packages only account for 2.8 to 10.9 percent of the total costs. Labor costs associated with data collection and processing account for the majority of total costs range between 86 and 90.8 percent. Data storage costs cannot be neglected (1.2 to 2.0 percent), especially when data services are charged annually. A breakdown of annual costs for the five-year time-horizon scenario is given in Table 6.

Table 5: Average Per-Bridge Costs by Service Option and Package

Service Option	Basic	Enhanced	Premium
P&O 5-year	$495	$612	$1,105
P&O 10-year	$479	$585	$1,018
P&O 15-year	$476	$581	$1,001
Contract	$1,300	$1,560	$2,860

Table 6: Annual Cost Breakdown for P&O Deployment Option (Five-Year Time Horizon, with Ten Percent of State-Owned Bridges Inspected each Year in Michigan)

Cost per bridge	Basic Package		Enhanced Package		Premium Package	
	Cost	% of Total	Cost	% of Total	Cost	% of Total
Capital investment per bridge	$14	2.8%	$29	4.8%	$120	10.9%
Vehicle cost per bridge	$22	4.4%	$22	3.6%	$22	2.0%
Operational data cost per bridge	$10	2.0%	$11	1.8%	$13	1.2%
Operational labor cost per bridge	$450	90.8%	$550	89.8%	$950	86.0%
Total	$495	100.0%	$612	100.0%	$1,105	100.0%

Figure 1: Cost per Bridge by Total Bridges Inspected for each Package under both Purchase-and-Operate (P&O) and Contracted Service Options
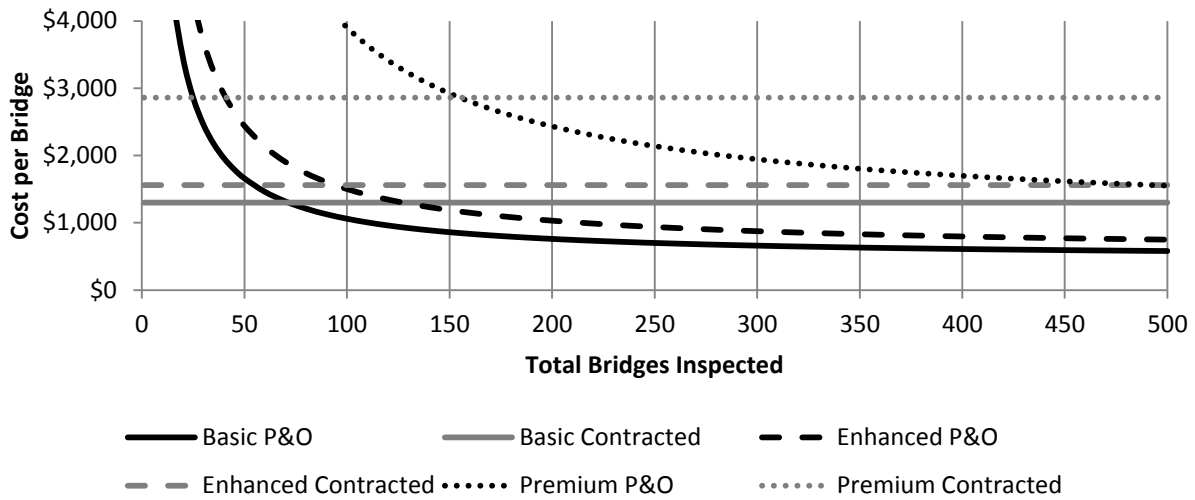
BENEFITS OF REMOTE SENSING TECHNOLOGIES

The economic evaluation of not-yet-deployed remote sensing technologies involves determining the value of rapidly evolving technologies or products (both hardware and software) in an environment in which market data from real-world practices is limited or non-existent. Further complicating evaluation is that the outcome indicators of traditional bridge inspections and those derived from using remote sensing technologies are often not directly comparable. From wider technical perspectives, however, the use of remote sensing technologies will have at least following beneficial consequences:

Novel Data

Each technology tested in this study has its own value in terms of providing useful data previously unavailable from routine inspections. Some of these marginal improvements can be achieved through low capital investment and can be integrated into regular bridge inspection practices with minimum additional operational costs. As suggested in previous sections, a combination of three remote sensing technologies or premier service package costs about $1,000 per bridge, but it has the highest added value because they can provide as many as 22 desired measurements of bridge deck surface, deck subsurface, girder surface, girder subsurface, and global metrics in a single run (Table 4).

Improved Data

Inspection costs in general are not that significant comparing to bridge investment because they represent less than four percent of bridge life-cycle costs (construction, maintenance, and rehabilitation etc.) The greater value of remote sensing technologies is the benefits of a more efficient bridge management system and new technical capabilities that will lead to timelier detection of problems, resulting in substantial cost savings and longer asset life – if these technologies become practical and cost-effective. Some of the effective diagnosis tools, such as ultra wide band imaging radar system (UWBIRS), are able to give early detection of bridge construction faults, defects, and the deterioration processes. Combined with advanced data processing and visualization tools, these remote sensing technologies can produce a surprising level

of information about the inner structure of a bridge. Additionally, the improved interpretability and accuracy of bridge condition assessments will definitely help bridge management agencies make better decisions and develop cost-effective maintenance strategies and procedures, including timely interventions to prevent bridge failures and to reduce life-cycle costs.

More Efficient Bridge Scoping

The outcome indicators of several of the remote sensing technologies field tested are similar to the outputs required in bridge scoping, such as measures of extent of delamination, spalling, and crack areas, and calculation of deterioration percentage—without costly traffic closures. These measures are critical input in developing repair strategies and cost estimates. MDOT scoped 167 bridges in 2010 with an average cost of about $9,300 per bridge. Using these technologies to supplement current inspection and analytical work, transportation agencies or engineering firms will likely complete bridge scoping with a smaller budget.

Safety

Remote sensing technologies have great safety implications for bridge inspectors when they can keep bridge inspectors out of traffic for both regular inspection and bridge scoping. The benefits are maximized when these new technologies are mounted on a vehicle and travel at close to highway speed.

Potential for Incorporation into Decision Support System (DSS)

The DSS is a web-accessible database application for accessing, visualizing and analyzing bridge condition information. This tool has been designed by the research team to be able to integrate existing historical bridge condition data typically collected and used by DOTs, as well as integrate the results of remote sensing technologies and create comprehensive bridge health signatures. Each bridge health signature becomes easily assessable and directly comparable.

Extracted features from remote sensing products, such as spalls or delaminations, can be stored as geospatial objects in a spatial database such as PostGIS so as to enable server-side analysis and processing (e.g., spatial intersects, zonal statistics).The DSS can also display clearly in mobile table-computers to make the DSS readily available to bridge inspectors and engineers in the field. In the end, DSS will enable more cost-efficient bridge asset management if used as part of MDOT planning processes.

CONCLUSIONS

The pressure to increase economic efficiency of transportation expenditures has created the necessity of data-driven, element-level bridge inspection programs and advanced Bridge Management Systems (USDOT, 2011). This in turn will lead to improved bridge management actions (i.e., maintenance, preservation, rehabilitation, replacement decisions). The use of remote sensing technologies presents a potential alternative to augment current practices by providing both qualitative and quantitative measures of a bridge's condition. To ensure a practical, cost-effective product to be integrated into transportation agency operations, this economic evaluation assessed the cost effectiveness of remote sensing technologies by comparing marginal costs of employing sensor technologies to the marginal enhancements that they provide.

The decision whether to deploy new remote sensing technologies is governed by their ability to yield new, reliable information on condition state of bridge elements. However, the benefits of remote sensing technologies can be optimized by deploying multiple technologies or premium service package at one time (e.g., using Thermal IR, 3DOBS, and UWBIRS together). Under several different deployment scenarios tested in the study, the average cost for using the premium service package was about $1,000 per bridge (or about $480 for Thermal IR only, and $580 for Thermal IR and 3DOBS). The capital cost (equipment and vehicle) accounted for less than ten percent. The majority was operational costs (labor cost associated with data collection and processing, data storage). The tipping point for two different deployment options (purchase and operate vs. contract service) ranged from 72 to 155 bridges, depending on the service option—meaning that it would become more cost effective for state agencies to purchase and operate when there are more than this number bridges to be inspected.

The benefits of any of the remote sensing technologies and deployment procedure will also depend on specific locations, types and number of bridges to be included, traffic, and other aspects. The cost effectiveness of remote sensing technologies is highly dependent on the successful integration with existing bridge inspections (both regular and bridge scoping). The decision support system (DSS) integrated with bridge condition data from remote sensing technologies will increase the accessibility of the data, and makes bridge condition comparisons easier and more accurate. It will also help decision making and resource allocation. It is likely that existing DOT inspection team will fulfill the new functions and responsibilities of using remote sensing technologies. Therefore, it is important to standardize data collection techniques, simplify data processing steps, and develop reporting procedures to encourage stakeholders' buy-in.

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