Economic Feasibility Study for Pavement Monitoring Using Synthetic Aperture Radar-Based Satellite Remote Sensing

Cost–Benefit Analysis

Mingxin Li, Ardeshir Faghri, Abdulkadir Ozden, and Yixiang Yue

Recent developments in satellite remote sensing and the availability of high-resolution synthetic aperture radar (SAR) products have created an opportunity for the use of SAR-based monitoring for pavement and infrastructure management. No previous studies have performed a detailed cost–benefit analysis to analyze the economic feasibility of pavement monitoring through the use of SAR-based satellite remote sensing. The aim of this study was to fill this knowledge gap by proposing a comprehensive methodology to estimate the most important benefits and expenses associated with the use of data obtained from satellites by SAR and interferometric SAR for advanced monitoring of the infrastructure and to gain a better understanding of the strategies used to identify their effects. A general cost–benefit analysis framework that could serve as a pavement management tool for assessment of pavement deformations and deformation velocities with millimeter accuracy was developed. The results of a case study performed in the state of Delaware to demonstrate how the proposed approaches can be used to assess the impacts of SAR-based monitoring projects are also presented.

The transportation infrastructure in the United States is aging, which emphasizes the importance of preserving existing assets and maintaining the transportation system at a sustainable level. Research indicates that 65% of U.S. roadways are rated in less than good condition and that 25% of U.S. bridges require significant repair (*1*). FHWA has estimated that an annual investment of \$77 billion is needed for the federal-aid highway system, whereas the receipts of the Federal Highway Trust Fund were only \$34 billion in 2014 (*2*). Furthermore, budget limitations and decreased revenues have made it extremely difficult for many states to maintain their roadways in a state of good repair.

Traditional pavement inspection techniques determine the condition of pavements through observation and recording, but these tasks make pavement survey work cumbersome and inefficient. In fact, some of these periodic inspection-based monitoring efforts are redundant, and some of them result in the late detection of problems, which results in the loss of money and excessive energy consumption.

M. Li, 355A DuPont Hall; A. Faghri, 360C DuPont Hall; and A. Ozden, 160 DuPont Hall, Department of Civil and Environmental Engineering, University of Delaware, Newark, DE 19716. Y. Yue, School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China. Corresponding author: M. Li, lmx@udel.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2645, 2017, pp. 1–11.
http://dx.doi.org/10.3141/2645-01

Therefore, any contribution to network-scale monitoring tools that facilitate the early detection of problems and reduce vehicle-based inspection trips to transportation infrastructure sites will help build more robust and effective monitoring programs (*3*).

In the past two decades, synthetic aperture radar (SAR) technology and interferometric SAR (InSAR) applications have been widely investigated for their use for large-scale monitoring. The fields in which SAR applications are mature have been summarized by Ouchi (*4*). The availability of high-resolution SAR images and advanced data processing methodologies has recently gained the attention of the transportation research community. With these developments, the extraction of information for the identification of problems and their extent at relatively small targets has become possible, and these developments make the technique useful for pavement and infrastructure monitoring.

However, many significant questions remain to be addressed, in particular, the costs that should be monitored and recorded and the quantitative and qualitative benefits that can be attained through investments in policies and initiatives, in particular, those related to evaluation of the use of SAR-based systems, data sources, and SAR image analysis tools for pavement and infrastructure monitoring. For example, how should the benefits of SAR image analysis tools for pavement and infrastructure monitoring be evaluated, and how can these investments be justified? Furthermore, how long would it take for an investment to pay for itself?

No previous study has performed a detailed cost–benefit analysis (CBA) of the economic feasibility of pavement monitoring by SAR-based satellite remote sensing. The aim of this study was to fill this knowledge gap by proposing a comprehensive methodology to estimate the most important benefits and expenses associated with the use of data from satellites equipped with SAR and InSAR for advanced monitoring of the transportation infrastructure and gain a better understanding of the strategies used to identify their effects.

The remainder of the paper is organized as follows. The next section describes the traditional technologies used for pavement and infrastructure monitoring. An overview of remote sensing by the use of SAR and current practices for evaluation of the transportation infrastructure by SAR-based remote sensing is then provided. The framework proposed for the performance of a CBA is discussed by introduction of the main inputs and outputs that may be used to estimate the most important benefits and expenses associated with SAR-based pavement monitoring. The results of a case study performed to determine whether the benefits of SAR-based pavement monitoring can justify the expenditure are also presented. Finally, the paper recommends research that needs to be performed, policies that could be made, and other measures that could be taken to meet the goals of SAR-based remote sensing for evaluation of the transportation infrastructure.

TRADITIONAL PAVEMENT AND INFRASTRUCTURE MONITORING TECHNOLOGIES

Pavement condition surveys provide an indication of the physical condition of pavements and consist of data collection, pavement condition rating, and quality management elements. Both manual data collection techniques (human observation) and automated data collection techniques (techniques that use line and area scanners, ground-penetrating radar, acoustic sensors, optical imagery, lidar, etc.) are widely used on the basis of an agency's priorities, available resources, and geographic limitations (*5, 6*). The condition ratings are then used to estimate the rehabilitation and maintenance work required and to manage that work, perform long-term economic planning, and prepare historical pavement performance records. A variety of pavement condition data have been collected; however, the most common type of data could be categorized as distress data, structural capacity data, ride quality data, and skid resistance data, as suggested by Attoh-Okine and Adarkwa (*7*). Distress and ride quality data were found to be relevant for consideration of the potential contribution of SAR-based monitoring.

Two critical challenges in pavement management are the timely detection of problems and the frequency of data collection. Many studies and the experiences of transportation agencies show that the early detection of problems and treatment with preventive measures increase the service life of the asset, reduce total maintenance costs, and maintain safety and quality (*8*). Haider et al. stated that "longer monitoring intervals may underpredict the expected roughness and overpredict the expected life on the basis of roughness" and highlighted the importance of the early detection of problems for the prediction of propagation (*9*). Therefore, an SAR-based continuous monitoring system might help with the development of a more robust method of pavement and infrastructure monitoring and reduce the number of routine vehicle-based inspection trips needed or allow such trips to be prioritized and thus reduce monitoring costs. Most agencies perform routine inspections of pavement and infrastructure elements, such as bridges, over different cycles (1 to 3 years), but monthly monitoring through the use of satellite imagery will contribute to routine monitoring efforts through the more frequent provision of data at the network level.

OVERVIEW OF SAR-BASED REMOTE SENSING AND CURRENT TRANSPORTATION INFRASTRUCTURE EVALUATION PRACTICES

This section describes studies of pavement monitoring and bridge assessment, since the use of SAR-based remote sensing in these two fields has increasingly been investigated.

Overview of SAR-Based Remote Sensing

SAR imagery is produced by measurement of the transmitted or backscattered radiation from the illuminated scene and contains both the amplitude and phase in each pixel. Amplitude is the measure of the radiation backscattered by the objects in each pixel, and phase measures the distance between the radar and the scene in proportion to the wavelength (λ) for the detection of surface deformations. The ability to penetrate clouds, operate during the day or at night, and work under all weather conditions makes SAR superior to other imaging techniques, especially at locations where severe climatic conditions may be encountered (*10, 11*). InSAR analysis requires determination of the phase difference, as presented in Equation 1:

$$\Delta\varphi = \Delta\varphi_{\text{displacement}} + \Delta\varphi_{\text{elevation}} + \Delta\varphi_{\text{flat}} + \Delta\varphi_{\text{atmosphere}} + \Delta\varphi_{\text{noise}} \tag{1}$$

where

$\Delta\varphi$ = interferometric phase;
$\Delta\varphi_{\text{displacement}}$ = contribution of surface deformation to the interferometric phase (the change is measured);
$\Delta\varphi_{\text{elevation}}$ = contribution of topographic effects to the interferometric phase;
$\Delta\varphi_{\text{flat}}$ = effect of the Earth's curvature on the interferometric phase (this effect can be estimated and subtracted);
$\Delta\varphi_{\text{atmosphere}}$ = contribution of the atmosphere to interferometric phase because of changes in temperature, humidity, and atmospheric pressure between acquisitions; and
$\Delta\varphi_{\text{noise}}$ = phase noise due to temporal changes in scatterers and the volume of scattering, look angles, and so forth.

Among these six components, $\Delta\varphi_{\text{displacement}}$ is expected to be accurately calculated through the removal or minimization of other effects.

The differential InSAR method has long been used for the detection of surface deformations, such as slow-moving landslides and volcanic and tectonic activity. Ferretti et al. introduced the permanent scatterers InSAR (PSInSAR) method for the effective removal of atmospheric interference through the use of stable neutral reflectors, such as buildings, transmission towers, and similar artificial objects, that have consistent radiation reflectivity in each SAR image over a series of images taken from the same scene and calculated surface deformations with millimeter accuracy (*12, 13*). However, the low density of permanent scatterers in nonurban areas encouraged researchers to use distributed scatterers to extract more information from the scene when PSInSAR was not applicable or not sufficient (*14–16*).

Because the InSAR method and advanced deformation detection techniques based on InSAR (such as the differential InSAR, PSInSAR, and SqueeSAR techniques) are able to measure surface deformations with millimeter accuracy (*11, 12*) and high-resolution satellite images can significantly increase the number of points detected (*17, 18*), satellite-based monitoring of the infrastructure for the detection of deteriorating roadways, such as bridge settlements and displacements, surface deformations, and sinkholes (*19–21*), or for the detailed analysis of targeted areas that are already known from previous studies to be problematic (*22*), could be possible. Satellite-based remote sensing technology is thus promising and is expected to play a crucial role in reducing the cost of network-scale pavement and infrastructure monitoring for state and federal agencies in the near future as high-resolution satellite imaging becomes more widely available and less costly and analysis methods and algorithms become more mature (*18, 19*).

Current Transportation Infrastructure Practices of SAR-Based Remote Sensing

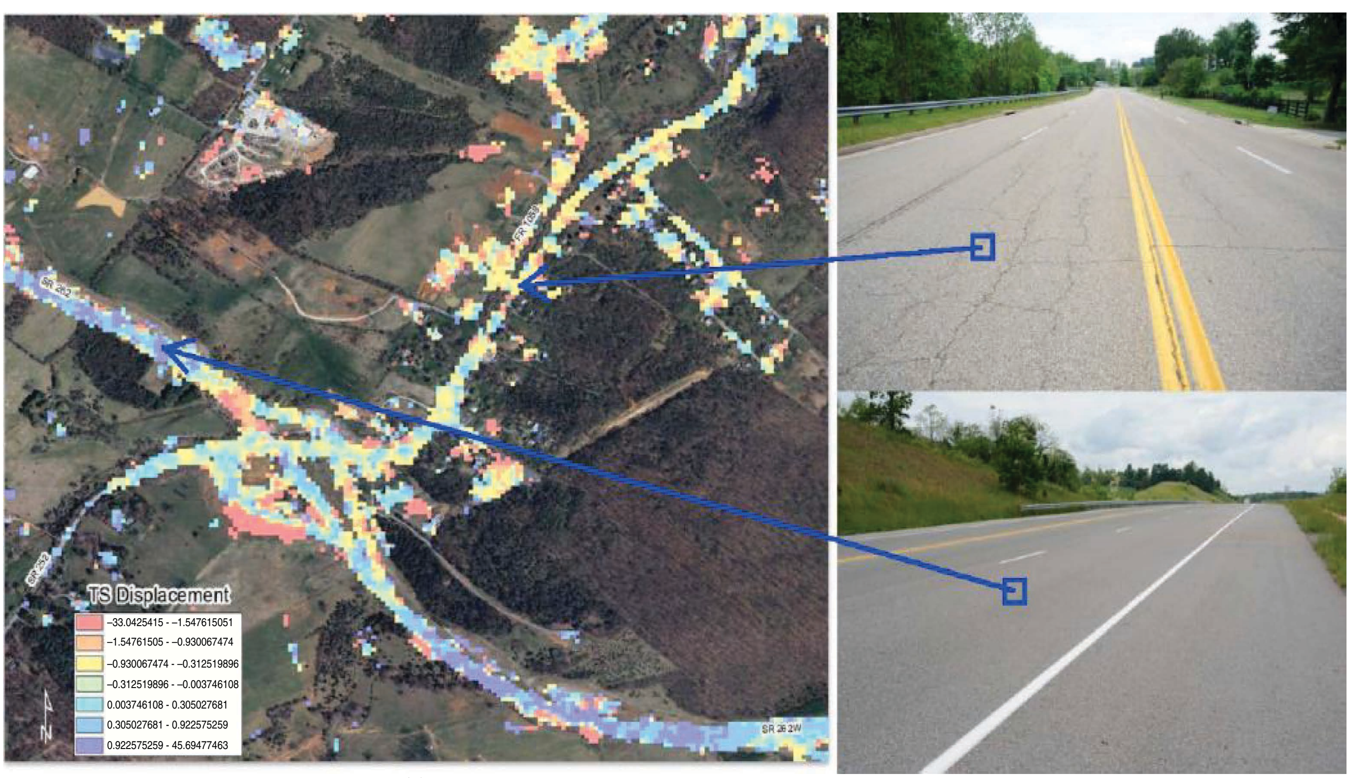
Recent studies have highlighted the effectiveness of InSAR methods for pavement and infrastructure monitoring. Cascini et al. compared medium- and high-resolution SAR images of a high-speed railway and a nearby highway section obtained by the PSInSAR method and concluded that the availability of high-resolution SAR images can significantly increase the accuracy of the results and the level of detail available for the detection of deformations (*18*). Bruckno et al. (*20*) and Hoppe and colleagues (*21*) found that both methods are useful for the detection of sinkhole formations, progressive settlements on bridges, and dangerous rock slopes. In the same study, they evaluated pavement surface distress with temporary scatterer raster data, highlighted the possible uses of such a technique, and recommended further exploration of the technique, as presented in Figure 1 (*20, 21*).

In another study, Hoppe et al. used the InSAR analysis technique to evaluate an ongoing water intrusion problem at both approaches to the Monitor–Merrimac Memorial Bridge–Tunnel in Virginia by using 46 medium- and high-resolution SAR images collected over a 10-year time frame and provided a good example of the use of historical satellite images for long-term evaluation (*22*). Suanpaga and Yoshikazu predicted pavement roughness with SAR imagery and found that single polarization backscatter values are correlated with the condition of the pavement (*23*).

One common result in the previously mentioned studies is that the researchers were not able to identify the type of pavement surface distress or settlement problems without further on-site investigation. This need for further on-site investigation is mainly the result of the limited research on the use of InSAR and InSAR-based methods available for use in the field of transportation and infrastructure monitoring. Nevertheless, InSAR has recently received the attention of the transportation and infrastructure research community. However, many of the studies did not specifically focus on the detection of pavement deformations but merely presented the results of studies with InSAR to show the potential contribution of SAR-based monitoring. Therefore, further research investigating the possible use of SAR-based applications specifically for pavement monitoring might provide more reliable information on the use of this technology for pavement management.

COST–BENEFIT ANALYSIS

In many CBAs that investigate the monetary effects of a possible new technology or data collection method, it is common to evaluate the cost in two parts: capital costs and maintenance and operating costs (*24–26*). Capital costs include one-time expenses, such as adaptation of a system and the associated technical infrastructure, computer and software costs, and new personnel. Maintenance and operating costs include ongoing or scheduled expenses that are incurred when the system is in use, such as the continuous acquisition of SAR-based imagery and data processing costs. A CBA of the adoption of satellite-based pavement and infrastructure monitoring should be approached from this perspective. In most cases, the cost of an SAR-based monitoring system is dominated by the cost of the SAR-based imagery, in which operational costs (personnel time, data storage, and data processing time) are much less than image costs (*27*).



(a) (b)

FIGURE 1 Pavement surface deformation detection with temporary scatterer (*21*) (TS = temporary scatterer).

Vavrik et al. evaluated manual and automated methods for the collection of pavement distress data to help the Ohio Department of Transportation determine whether the transition from a manual system to a semiautomated or fully automated system would be reasonable (*28*). In that study, inputs from six vendors and 18 state agencies helped provide comprehensive and reliable data for a comparative analysis, including a detailed cost analysis.

In a study conducted by Hong et al., commercial remote sensors were evaluated to determine and compare the costs of eight technologies widely used to monitor bridge health, including the BridgeViewer remote camera system, lidar, and SAR (*29*). First, a basic comparative analysis was conducted on the basis of a literature review and interviews with experts in the field. Then, a detailed analysis of the costs of various elements, such as the data collection system, the data collection vehicle, data storage, data processing time, and the contractor, was conducted. In total, the costs of seven technologies available at the time that the study was conducted were compared. Although that study excluded an analysis of the cost of the SAR technology, the benefits and limitations of that method were briefly presented. The SAR method was found to be useful for the detection of bridge settlement and determination of road and bridge surface roughness. The limitations of the SAR technology included the need for the continuous acquisition of SAR data to evaluate the before and after situations and the need for high-quality SAR images for the analysis of roughness.

In another study, Vaghefi et al. reviewed commercially available bridge monitoring technologies in detail and rated them on the basis of their cost, the availability of instruments, their data processing complexity, traffic disruption, and so forth, and gave them scores ranging from 0 to 16, in which a score of 16 meant that all criteria were met with high scores (*27*). The InSAR method was found to be useful for determination of the global metrics of bridges, such as bridge length, bridge settlement, bridge movement, surface roughness, and vibration, and received scores of 12 and above for all criteria.

In the present study, a CBA of SAR-based pavement and infrastructure monitoring was conducted (Figure 2). It was assumed that SAR-based monitoring efforts will be complementary to current monitoring efforts and will not replace those efforts. It is expected that SAR-based monitoring will reduce unnecessary vehicle-based site inspection trips and that the monitoring effort providing continuous SAR-based imagery will allow prioritization for the timely detection of pavement and infrastructure problems. No previous study has evaluated or quantified the possible reduction in routine vehicle-based inspection trips as a result of the use of SAR-based continuous monitoring. Therefore, some assumptions were used here to provide insight for further studies. In addition, in this CBA, the findings of a previous study were used to estimate the cost of pavement distress monitoring (*28*).

Cost Scenarios

Unit Costs of Development of Technical Infrastructure for SAR-Based Data Analysis

Computer and software are the main elements requiring capital costs for SAR-based monitoring. However, because many departments of transportation are already equipped with computers with high-level processing capabilities and common software, such as geographic information system and computer-assisted drafting software, the

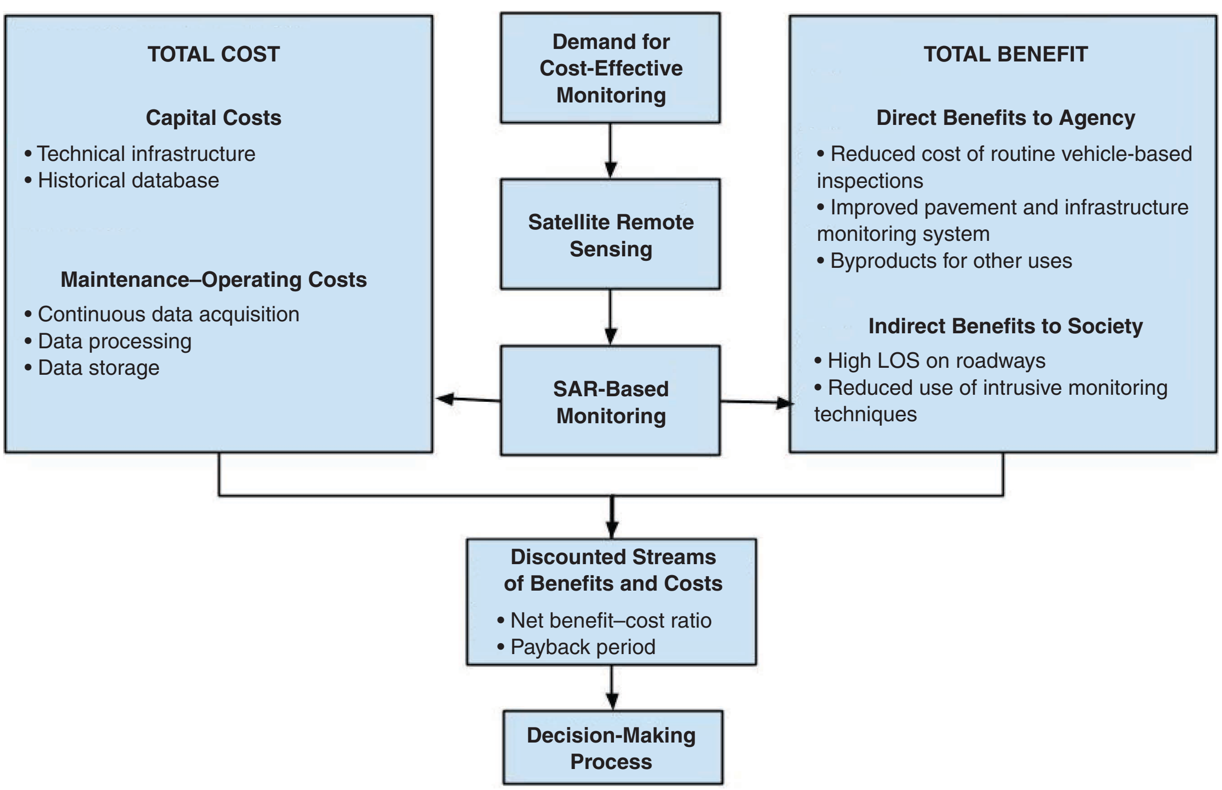


FIGURE 2 Conceptual framework of CBA (LOS = level of service).

costs of these items might not need to be included in the CBA. Nevertheless, the unit cost for the purchase of computer and software is assumed to range from \$10,000 to \$15,000. Computer and software costs will be accounted for every 5 years because of technological advancements and licensing.

The data storage cost is also accounted for because each SAR image and its byproducts require between 5 and 10 gigabytes. If an agency decides to obtain historical data when it adopts the system, initial data storage will be necessary. The cost of data storage was previously estimated to be \$10 per gigabyte per year (*29*). Therefore, if it is assumed that each SAR image, including some processing byproducts, uses 5 to 10 gigabytes, a safe estimate of the data storage cost for 20 SAR images is \$1,500 per year and a \$3,000 capital cost for the storage of historical data will be required. This process might also be excluded on the basis of the data storage capability of an agency. Another capital cost at the beginning stage of adoption of SAR-based monitoring will be the training of personnel for data processing. This cost is estimated to be a one-time expense of \$50,000.

Unit Costs of SAR-Based Image Acquisition and Processing

The costs of SAR images and data processing may vary depending on the technical features of the image (medium or high resolution); the size of the area of interest; and the data processing methods used, such as InSAR, PSInSAR, and SqueeSAR (the latest time series InSAR technique, which is referred to as TSInSAR). Some agencies prefer to outsource image acquisition and processing and receive the end products as geographic information system and computer-assisted drafting software files for the further evaluation of a specific project. However, because of the possible high cost required to outsource the process, an agency might prefer to establish the necessary technical infrastructure for image acquisition and processing in-house, which might significantly reduce operating costs in the long term.

In addition, if the SAR-based monitoring method is used for a specific project or is used temporarily, Power et al. suggested that a feasibility study be conducted to test the coherence of images before proceeding further to reduce the cost of image acquisition (*30*). The authors stated that four images could be used in a feasibility study to test the coherence of the images.

Airbus Defence and Space provides information on the cost of high-resolution satellite images along with the data processing costs that applied in 2014 (*31*). The cost of image acquisition varies depending on the product requested (e.g., the SpotLight, StripMap, and ScanSAR InSARs), the scene size, and delivery options, in which customers might request fast or urgent delivery for a fee. For InSAR analysis, SpotLight InSAR and StripMap InSAR data stacks are available for purchase. The data provider also requires the purchase of a minimum of five scenes for the stack packages for the following discounted InSAR stack prices: €2,500 per scene for a minimum of five scenes for the SpotLight InSAR and €1,250 per scene for a minimum of five scenes for the StripMap InSAR (€1 was equal to US\$1.11 in 2015).

Like most InSAR contractors, Airbus Defence and Space also quotes the cost of image acquisition and data processing as a package on the basis of customer needs and the physical properties of the area of interest because of the complexity of the data processing and the availability of analysis methods (*31*). The cost of such a package is mostly determined on the basis of discussions between the customer and the contractor. In some cases, contractors perform a preliminary site analysis and an evaluation of coherence before providing the cost to the customers. It is also possible for contractors to provide a fixed base price for InSAR analysis independently of the complexity of the project (*30*). The cost of high-resolution Cosmo-SkyMed SAR images and data processing is provided below. This cost includes the cost for data processing but does not include the cost of fast processing and delivery fees, which may vary (*32*).

1. For Spotlight-2 InSAR images of 7×7 km at a 1-m resolution, €9,450 for new images and €4,725 for archived images;
2. For Spotlight-2 InSAR images of an area 10×10 km at a 1-m resolution, €6,150 for new images and €3,075 for archived images; and
3. For a strip map of an area 40×40 km at a 5-m resolution, €3,600 for new images and €1,800 for archived images.

Medium-resolution SAR images cost less than high-resolution images for InSAR analysis. However, these types of images are mostly preferred for large-scale deformation analysis and historical monitoring. Power et al. stated that historically archived data covering a time frame of an average of 3 to 5 years with minimum of 15 or more images can produce results of high accuracy for monitoring programs (*30*).

Power et al. reported that the estimated cost of medium-resolution images is as follows: for ERS or ENVISAT satellite images, \$1,000 per image for an area of 100×100 km (60×60 mi), and for RADARSAT-1 satellite images, \$2,500 per image for an area of 50×50 km (30×30 mi) (*30*).

The cost of image acquisition highly depends on the total number of images purchased, and significant discounts, such as discounts of 50% to 75%, might reduce the overall cost when increased quantities are purchased.

Power et al. reported that the estimated costs of image processing are as described below (*30*).

1. For a feasibility study:
   - SAR imagery (ERS or ENVISAT satellite) = 4 images × \$1,000 = \$4,000;
   - Generation of coherence images (2 person days) = \$2,000; and
   - Generation of a report of the feasibility study (2 person days) = \$2,000.
2. For ongoing costs per monitoring interval:
   - Ground movement maps generated by the use of the RADARSAT-1 satellite,
     - SAR imagery = 2 images × \$2,500 = \$5,000, and
     - InSAR deformation map generation (2 to 10 person days) = \$2,000 to \$10,000;
   - Ground movement maps generated by the use of the ERS or ENVISAT satellite,
     - SAR imagery = 2 images × \$1,000 = \$2,000, and
     - InSAR deformation map generation (2 to 10 person days) = \$2,000 to \$10,000.

Costs Not Included in the Model

The costs associated with the building of a technical infrastructure for the data processing unit in an agency, such as the cost of network connections, printers, and scanners, were ignored because most of these items are already used in most agencies and their cost is insignificant compared with other capital costs.

Benefit Scenarios

As in all pavement and infrastructure monitoring applications, the primary goal of the use of the satellite-based remote sensing technology is the early detection of problems that might affect the safety and serviceability of the transportation network, the cost for maintenance and rehabilitation of which would later be much higher. From this perspective, the benefits of such a technology to the community, in addition to the benefits to the responsible agency, are crucial.

Direct Benefits to the Agency

The use of the satellite-based remote sensing technology might reduce the need for trips for routine pavement and bridge inspection, as the technology would regularly monitor the transportation infrastructure system at the network level. This monitoring will help the agency prioritize the vehicle-based inspection trips needed and reduce the use of other technologies, specifically, if it contracts for the use of other technologies.

For instance, it has been estimated that the contractor's charge to monitor bridge health is $1,300 and $1,800 when a mobile lidar system and an ultra-wide-band imaging radar system (a type of ground-penetrating radar system), respectively, are used (*29*). Because of the limited availability of data, it is assumed that SAR-based pavement and infrastructure monitoring might reduce the number of routine vehicle-based inspection trips by 5% to 20%. However, agencies that do not outsource the collection of data on the condition of pavements and the infrastructure might be able to purchase fewer vehicles or operate vehicles that they have already purchased less than usual because of the efficiency of the pavement and infrastructure monitoring system. This will eventually contribute to reductions in operational costs for the agency.

Indirect Benefits to Society

One of the main benefits expected from the use of a satellite-based remote sensing technology is maintenance of a high level of service on roadways. Maintenance of a high level of service will be possible because of the early detection of problems that might later cause major rehabilitation or maintenance issues, all of which will eventually result in the loss of time and money and excessive energy consumption. Chatti and Zaabar performed enhanced studies of initial studies on the effect of pavement surface condition on fuel consumption, tire wear, repair and maintenance costs, and vehicle operating costs (*33*). They presented cost adjustment factors on the basis of the change in the international roughness index of from 1 to 6 m/km in 1-m/km increments for three speed categories (35, 55, and 70 mph) and different vehicle classes. They reported that an increase in the international roughness index of 1 m/km (63.4 in./mi) increases fuel consumption by 2% for passenger vehicles and 1% to 2% for heavy trucks and increases repair and maintenance costs by 10% for passenger vehicles and heavy trucks after a certain level of roughness (*33*).

Indirect Benefits Not Quantified in the Model

One major problem with the evaluation of the benefits of the satellite-based remote sensing technology might be the lack of consideration of the broad range of users of the technology. Many departments and units, such as transportation planning, land development, and environmental offices, might benefit from the end products of a satellite-based monitoring program. These indirect benefits were not included in this study. Only benefits that might directly be related to the evaluation of pavement and bridge conditions were included.

The following is an example of indirect benefits: the State of Idaho started using satellite imagery to monitor water use in irrigation districts. Fifteen Landsat images were used to monitor water rights during the growing season and cost $30,000 annually, including staff time, whereas the conventional methods used previously cost half a million dollars (*34*).

Case Study for CBA

In the case study described, the applicability of satellite-based remote sensing technology to all bridges and federal aid highways in New Castle County in the state of Delaware was evaluated (Figure 3). This will help provide an understanding of the costs and benefits associated with SAR-based pavement and infrastructure monitoring. New Castle County contains the majority of the traffic and the road network in Delaware as well as the majority of the population of Delaware. Since satellite-based remote sensing technology will be used, the box area of New Castle County was used for cost estimation. New Castle County is approximately 24 mi (40 km) wide and 37 mi (60 km) long. Because Cosmo SkyMed SAR images come in scenes of 40 × 40 km, a minimum of two scenes will be required to cover all roadways in New Castle County.

FIGURE 3 New Castle County study area.

New Castle County has 492 state-owned bridges whose lengths make them part of the National Bridge Inventory. In 2014, 21 of these bridges were structurally deficient and 96 of them were functionally obsolete (*35*). The state also maintains 40.6 mi of Interstate highways, 1,874 mi of urban roadways, and 579 mi of rural roadways in New Castle County.

The cost estimates were developed by calculation of rough quantities and application of unit costs. The costs were then translated into the cost per mile or per category. All adjusted cost values were normalized to a base year of 2016. Inflation factors were developed on the basis of the producer price index for highway and street construction from data from 1986 to 2010 to convert unit costs from 2016 levels to the build year.

In this study, cost alternatives were investigated on the basis of three options and three resolution levels, as follows:

Option 1. Purchase data and perform data processing in-house.
Option 2. Purchase data and outsource data processing.
Option 3. Outsource data collection and data processing.

Resolution Level H. High resolution (7 × 7 km, 1-m resolution, €9,450 for new images and €4,725 for archived images).

Resolution Level M. Medium resolution (10 × 10 km, 1-m resolution, €6,150 for new images and €3,075 for archived images).

Resolution Level L. Low resolution (40 × 40 km, 5-m resolution, €3,600 for new images and €1,800 for archive images).

Estimation of the costs in this study involved several assumptions, including the following: (*a*) costs are based on standard facilities constructed in the United States and are represented in year 2016 dollars (they may change because of future economic conditions), and (*b*) the discount rate is 5% with a standard time horizon of 20 years (2016 to 2035) (Figure 4).

The results of the CBAs presented in Table 1 are based on a discount rate of 5% and a 20-year project lifetime. The benefit–cost ratios presented in Table 1 indicate that SAR-based monitoring systems could be cost-effective and that the cost of the system is quickly paid back for products of 10 × 10 km and 40 × 40 km. Even though the low-resolution images (40 × 40 km, 5-m resolution) had the highest benefit–cost ratio, it was useful only for the detection of sinkhole formations and thus could not be used to identify clearly the distress type in a pavement surface. When the spatial resolution and high benefit–cost ratio were considered, purchase of the SAR imagery and in-house processing option (Scenario 1M in Table 1) would be good for SAR-based pavement and infrastructure monitoring. The estimated cost to implement this plan over 20 years would be approximately $12.6 million (on the basis of 2016 dollars). The cost of the plan includes approximately $10.2 million for image purchase, $100,000 for computer and software purchases and data storage, and $200,000 for the training of personnel. The level of investment that would be required to implement this project is relatively modest in comparison with that of other transportation facilities. As shown in Table 1, the benefit–cost ratio equals 1.34, which means that this scenario leads to appealing results for the investment. Hence, an investment for the purchase of medium-resolution data and in-house data processing indeed seems to be beneficial to society. To illustrate the financial results, the economics of Scenario 1M were evaluated and compared with those of the other scenarios by the use of general profitability criteria, such as discounted cash flow and discounted payback period.

Apart from the benefit–cost ratio, the discounted cash flow was also calculated. To make a better strategic choice, it is essential to

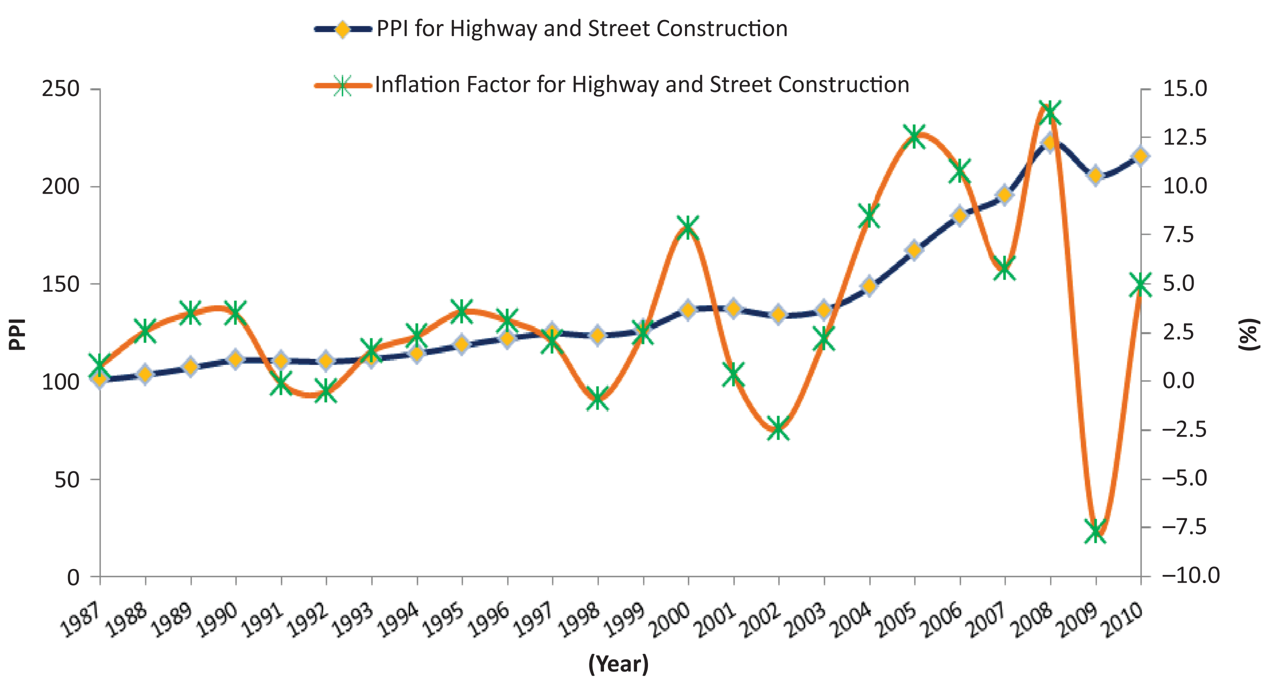


FIGURE 4 Producer price index (PPI) for highway and street construction, 1987 to 2010 (the value for 1986 is 100). (Source: Bureau of Labor Statistics.)

TABLE 1 Benefit and Cost Components of Investments, 2016 to 2035

Benefit and Cost	Value ($) 1H	1M	1L
Benefit (reduced cost, present value)	16,891,509	16,891,509	16,891,509
Total benefit	16,891,509	16,891,509	16,891,509
Costs (present value)			
Computer and software purchase	40,000	40,000	40,000
Data storage cost	60,000	60,000	60,000
Training personnel	200,000	200,000	200,000
Image purchase	32,569,898	10,205,618	459,540
Image processing	0	0	0
Total budget costs	32,869,898	10,505,618	759,540
Tax-cost factor, 20% of budget costs	6,573,980	2,101,124	151,908
Total cost	39,443,877	12,606,741	911,448
Benefit–cost ratio	0.43	1.34	18.53

NOTE: 1H = Option 1 and high resolution; 1M = Option 1 and medium resolution; 1L = Option 1 and low resolution; 2H = Option 2 and high resolution; 2M = Option 2 and medium resolution; 2L = Option 2 and low resolution; 3H = Option 3 and high resolution; 3M = Option 3 and medium resolution; 3L = Option 3 and low resolution.

analyze the economics of a proposed project in the capital budgeting process by the use of multiple tools such as discounted cash flow techniques that focus on the evaluation of cash flows by methods that take into account the time value of money. In this way, the model is able to measure the discounted cash flow over different periods to have a common basis of comparison. Figure 5 shows the estimated discounted payback period, and Figure 6 shows the discounted cash flow over different years. This scenario pays back the cost of the SAR system in 5 years when a 20-year time horizon is considered (Figure 6).

CONCLUSIONS

When limited economic resources are considered, the importance of cost-effective and reliable methods to support the monitoring and management of transportation infrastructure systems cannot be overemphasized. This research investigated the possible use of a satellite-based remote sensing technology, specifically SAR, for pavement and infrastructure monitoring and its contribution to such activities. Recent studies indicated the usefulness of this technology for determination of the location and severity of pavement and infrastructure problems at a certain level; however, no study has yet differentiated the problems on the basis of different types of pavements and infrastructures. Pavement and infrastructure monitoring-related methods are still in the development stage, and further research is needed.

SAR-based methods are highly effective for the detection of surface deformations and determination of deformation velocities with millimeter accuracies. This highly sensitive deformation detection ability may be useful specifically for the monitoring of bridge health. At present, SAR-based monitoring for pavement and infrastructure management has been found to be useful as a complementary tool to improve the effectiveness of the overall monitoring system and to reduce the total cost of monitoring rather than as a replacement for

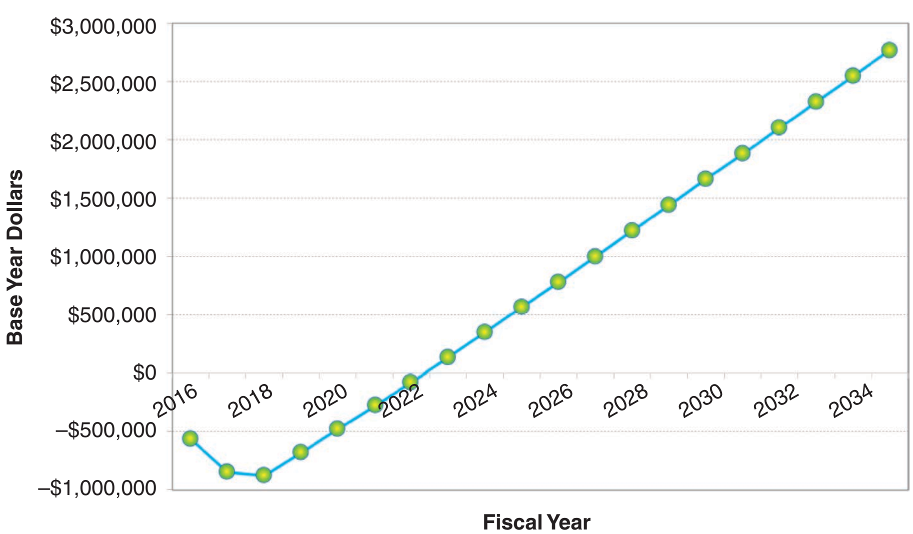


FIGURE 5 Estimated discounted payback period, Option 1M.

2H	2M	2L	3H	3M	3L
16,891,509	16,891,509	16,891,509	16,891,509	16,891,509	16,891,509
16,891,509	16,891,509	16,891,509	16,891,509	16,891,509	16,891,509
0	0	0	0	0	0
60,000	60,000	60,000	60,000	60,000	60,000
40,000	40,000	40,000	4,000	4,000	4,000
32,569,898	10,205,618	459,540	32,569,898	10,205,618	459,540
3,256,990	1,020,562	45,954	1,628,495	510,281	22,977
35,926,887	11,326,179	605,494	34,262,392	10,779,898	546,517
7,185,377	2,265,236	121,099	6,852,478	2,155,980	109,303
43,112,265	13,591,415	726,593	41,114,871	12,935,878	655,820
0.39	1.24	23.25	0.41	1.31	25.76

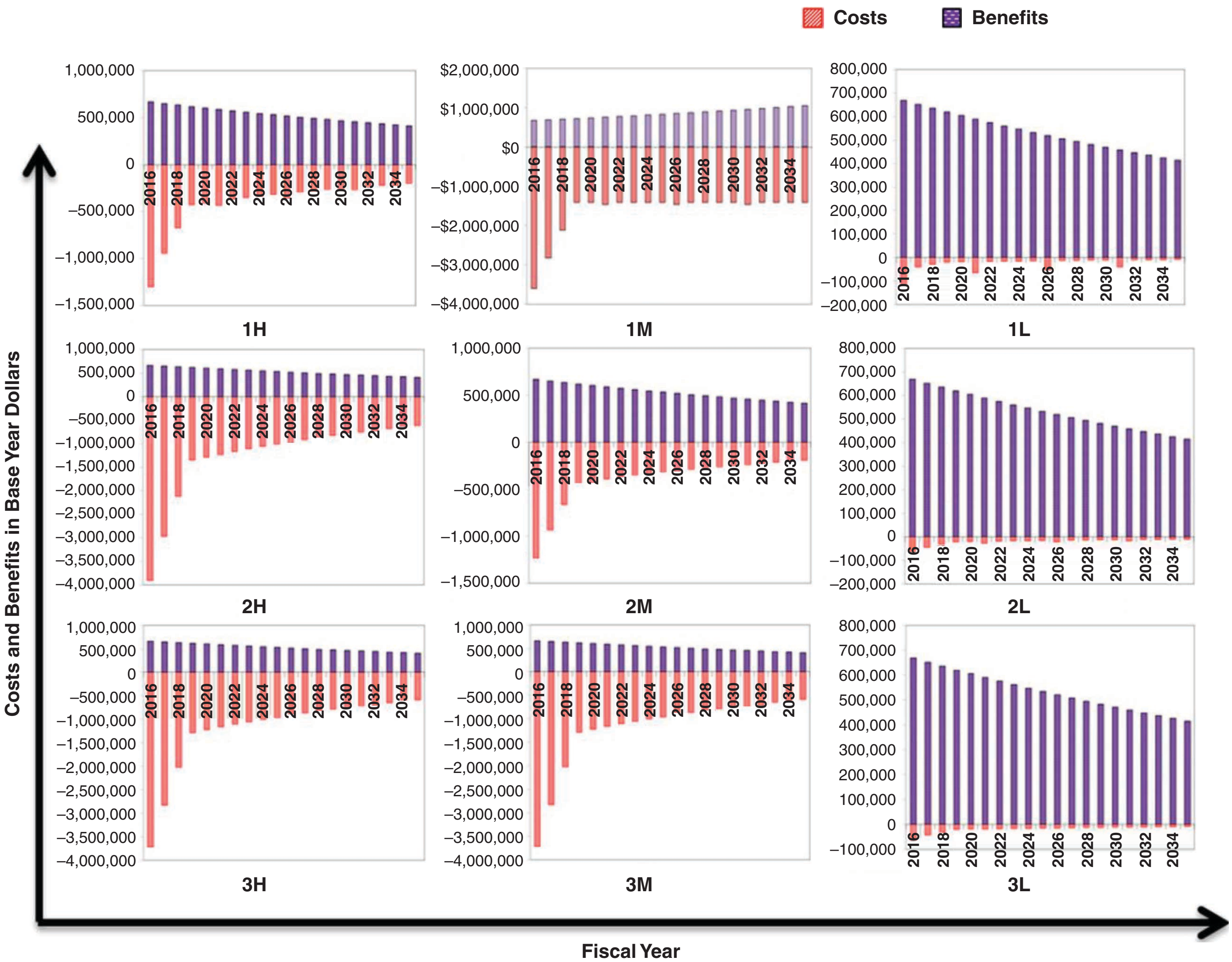


FIGURE 6 Discounted cash flow (the discount rate is 5%, 2016 to 2035; the scenarios are defined in the note to Table 1).

conventional methods, but its usefulness may change with advancements in the technology. Moreover, use of this approach will directly contribute to the U.S. Department of Transportation's strategic goals of maintaining pavements and the infrastructure in a state of good repair and economic competitiveness.

The complexity of SAR image types and features requires extra attention in the evaluation of the available and appropriate data sources for pavement and infrastructure monitoring. In addition to data selection, image processing should also be carefully carried out for the accurate calculation of deformation and deformation velocities. SAR-based monitoring and the end products of data analysis might also be helpful to many other departments and agencies in a region and help them save costs. Therefore, cooperation and collaboration within and between departments and agencies will reduce the total cost of monitoring and SAR data analysis efforts and will increase the overall benefits.

The scope of this research is limited to evaluation of the economic feasibility of the use of SAR-based systems, data sources, and SAR image analysis tools for pavement and infrastructure monitoring in general. The scope does not include an evaluation of the effectiveness of such systems for the detection of pavement surface distresses and infrastructure problems of different types and severities that require further exploration. In addition, certain conservative assumptions had to be made to improve the potential accuracy of the CBA. Only benefits that might directly be related to the evaluation of the conditions of pavements and bridges were included. Many departments and units might benefit from the end products of a satellite-based monitoring program, such as transportation planning, land development, and environmental offices. These indirect benefits need to be addressed by further research.

ACKNOWLEDGMENTS

This work was supported by the Center for Advanced Infrastructure and Transportation at Rutgers University through the National University Transportation Center Program. The program is funded by the U.S. Department of Transportation.

REFERENCES

1. *An Economic Analysis of Transportation Infrastructure Investment.* Executive Office of the President, 2014. http://www.whitehouse.gov/sites/default/files/docs/economic_analysis_of_transportation_investments.pdf. Accessed May 10, 2015.
2. *Beyond Traffic: Trend and Choices 2045.* U.S. Department of Transportation, 2015. https://cms.dot.gov/sites/dot.gov/files/docs/Draft_Beyond_Traffic_Framework.pdf.
3. Ozden, A., A. Faghri, and M. Li. Using Knowledge-Automation Expert Systems to Enhance the Use and Understanding of Traffic Monitoring Data in State DOTs. *Procedia Engineering,* Vol. 145, 2016, pp. 980–986. http://dx.doi.org/10.1016/j.proeng.2016.04.127.
4. Ouchi, K. Recent Trend and Advance of Synthetic Aperture Radar with Selected Topics. *Remote Sensing,* Vol. 5, No. 2, 2013, pp. 716–807. http://dx.doi.org/10.3390/rs5020716.
5. Faghri, A., M. Li, and A. Ozden. *Satellite Assessment and Monitoring for Pavement Management.* Center for Advanced Infrastructure and Transportation, State University of New Jersey, Piscataway, 2015.
6. Ozden, A., A. Faghri, M. Li, and K. Tabrizi. Evaluation of Synthetic Aperture Radar Satellite Remote Sensing for Pavement and Infrastructure Monitoring. *Procedia Engineering,* Vol. 145, 2016, pp. 752–759. http://dx.doi.org/10.1016/j.proeng.2016.04.098.
7. Attoh-Okine, N., and O. Adarkwa. *Pavement Condition Surveys—Overview of Current Practices.* Delaware Center for Transportation, University of Delaware, Newark, 2013.
8. *AASHTO Guidelines for Pavement Management Systems.* AASHTO, Washington, D.C., 1990.
9. Haider, S., K. Chatti, G. Baladi, and N. Sivaneswaran. Impact of Pavement Monitoring Frequency on Pavement Management System Decisions. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2225, 2011, pp. 43–55.
10. Bamler, R., and P. Hartl. Synthetic Aperture Radar Interferometry. *Inverse Problems,* Vol. 14, No. 4, 1998, pp. R1–R54. http://dx.doi.org/10.1088/0266-5611/14/4/001.
11. Ferretti, A., A. Monti-Guarnieri, C. Prati, F. Rocca, and D. Massonet. *InSAR Principles—Guidelines for SAR Interferometry Processing and Interpretation,* Vol. 19. European Space Agency Publication, Noordwijk, Netherlands, 2007.
12. Ferretti, A., C. Prati, and F. Rocca. Permanent Scatterers in SAR Interferometry. *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 39, No. 1, 2001, pp. 8–20. http://dx.doi.org/10.1109/36.898661.
13. Ferretti, A., G. Savio, R. Barzaghi, A. Borghi, S. Musazzi, F. Novali, C. Prati, and F. Rocca. Submillimeter Accuracy of InSAR Time Series: Experimental Validation. *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 45, No. 5, 2007, pp. 1142–1153. http://dx.doi.org/10.1109/TGRS.2007.894440.
14. Morgan, J., G. Falorni, A. Bohane, and F. Novali. Advanced InSAR Technology (SqueeSAR) for Monitoring Movement of Landslides. Publication FHWA-CFL/TD-11-005. FHWA, U.S. Department of Transportation, 2011.
15. Ferretti, A., A. Fumagalli, F. Novali, C. Prati, F. Rocca, and A. Rucci. A New Algorithm for Processing Interferometric Data-Stacks: SqueeSAR. *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 49, No. 9, 2011, pp. 3460–3470. http://dx.doi.org/10.1109/TGRS.2011.2124465.
16. Goel, K., and N. Adam. A Distributed Scatterer Interferometry Approach for Precision Monitoring of Known Surface Deformation Phenomena. *IEEE Transactions on Geoscience and Remote Sensing,* Vol. 52, No. 9, 2014, pp. 5454–5468. http://dx.doi.org/10.1109/TGRS.2013.2289370.
17. Bianchini, S., F. Cigna, C. Del Ventisette, S. Moretti, and N. Casagli. Detecting and Monitoring Landslide Phenomena with TerraSAR-X Persistent Scatterers Data: The Gimigliano Case Study in Calabria Region (Italy). *Proceedings of the IEEE International Geoscience and Remote Sensing Symposium,* Munich, Germany, 2012, pp. 982–985. http://dx.doi.org/10.1109/IGARSS.2012.6351237.
18. Cascini, L., D. Peduto, D. Reale, L. Arena, S. Ferlisi, S. Verde, and G. Fornaro. Detection and Monitoring of Facilities Exposed to Subsidence Phenomena via Past and Current Generation SAR Sensors. *Journal of Geophysics and Engineering,* Vol. 10, No. 6, 2013, p. 064001. http://dx.doi.org/10.1088/1742-2132/10/6/064001.
19. Schnebele, E., B.F. Tanyu, G. Cervone, and N. Waters. Review of Remote Sensing Methodologies for Pavement Management and Assessment. *European Transport Research Review,* Vol. 7, No. 2, 2015, pp. 7–19. http://dx.doi.org/10.1007/s12544-015-0156-6.
20. Bruckno, B., A. Vaccari, E. Hoppe, W. Niemann, and E. Campbell. Validation of Interferometric Synthetic Aperture Radar as a Tool for Identification of Geohazards and At-Risk Transportation Infrastructure. *Proceedings of the 64th Highway Geology Symposium,* Red Hook, N.Y., 2013, pp. 415–433.
21. Hoppe, E., B. Bruckno, E. Campbell, S. Acton, A. Vaccari, M. Stuecheli, A. Bohane, G. Falorni, and J. Morgan. Transportation Infrastructure Monitoring Using Satellite Remote Sensing. *Proceedings of the Transport Research Arena (TRA) 5th Conference: Transport Solutions from Research to Deployment,* Paris, 2014.
22. Hoppe, E.J., Y.J. Kweon, B.S. Bruckno, S.T. Acton, L. Bolton, A. Becker, and A. Vaccari. Historical Analysis of Tunnel Approach Displacements with Satellite Remote Sensing. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2510, 2015, pp. 15–23. http://dx.doi.org/10.3141/2510-03.
23. Suanpaga, W., and K. Yoshikazu. Riding Quality Model for Asphalt Pavement Monitoring Using Phase Array Type L-Band Synthetic Aperture Radar (PALSAR). *Remote Sensing,* Vol. 2, No. 11, 2010, pp. 2531–2546. http://dx.doi.org/10.3390/rs2112531.
24. Li, M., and A. Faghri. Cost–Benefit Analysis of Added Cycling Facilities. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2468, 2014, pp. 55–63. http://dx.doi.org/10.3141/2468-07.

25. Li, M., and A. Faghri. Applying Problem-Oriented and Project-Based Learning in a Transportation Engineering Course. *Journal of Professional Issues in Engineering Education and Practice,* Vol. 142, No. 3, 2016, p. 04016002. http://dx.doi.org/10.1061/(ASCE)EI.1943-5541.0000274.
26. Lichliter, A., A. Faghri, and M. Li. Assessing Airport Snow and Ice Removal and Its Economic Implications for Sustainable Airport Management. *Journal of Airport Management,* Vol. 8, No. 2, 2014, pp. 174–188.
27. Vaghefi, K., R.C. Oats, D.K. Harris, T.T.M. Ahlborn, C.N. Brooks, K.A. Endsley, C. Roussi, R. Shuchman, J.W. Burns, and R. Dobson. Evaluation of Commercially Available Remote Sensors for Highway Bridge Condition Assessment. *Journal of Bridge Engineering,* Vol. 17, No. 6, 2011, pp. 886–895. http://dx.doi.org/10.1061/(ASCE)BE.1943-5592.0000303.
28. Vavrik, W.R., L.D. Evans, J.A. Stefanski, and S. Sargand. *PCR Evaluation—Considering Transition from Manual to Semi-Automated Pavement Distress Collection and Analysis.* Ohio Department of Transportation, Columbus, 2013, p. 29.
29. Hong, Q., R. Wallace, T.M. Ahlborn, C.N. Brooks, E.P. Dennis, and M. Forster. Economic Evaluation of Commercial Remote Sensors for Bridge Health Monitoring. Presented at 92nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2013.
30. Power, D., J. Youden, J. English, K. Russell, S. Croshaw, and R. Hanson. INSAR Applications for Highway Transportation Projects. Publication FHWA-CFL/TD-06-002. FHWA, U.S. Department of Transportation, 2006.
31. *TerraSAR-X Services International Price List.* Airbus Defence and Space, 2014. http://www2.geo-airbusds.com/files/pmedia/public/r463_9_itd-0508-cd-0001-tsx_international_pricelist_en_issue_6.00.pdf.
32. Price List. e-GEOS, 2016. http://www.e-geos.it/products/pdf/prices.pdf.
33. Chatti, K., and I. Zaabar. *NCHRP Report 720: Estimating the Effects of Pavement Condition on Vehicle Operating* Costs. Transportation Research Board of the National Academies, Washington, D.C., 2012. http://dx.doi.org/10.17226/22808.
34. Kalluri, S., P. Gilruth, and R. Bergman. The Potential of Remote Sensing Data for Decision Makers at the State, Local and Tribal Level: Experiences from NASA's Synergy Program. *Environmental Science & Policy,* Vol. 6, No. 6, 2003, pp. 487–500. http://dx.doi.org/10.1016/j.envsci.2003.08.002.
35. Giuffre, W.L. Evaluation of Highway Performance Measures for a Multi-State Corridor—A Pilot Study. FHWA, U.S. Department of Transportation, 2010.

The Standing Committee on Geospatial Data Acquisition Technologies peer-reviewed this paper.