Chapter

Environmentally Influenced Risk and Sustainable Management of State Controlled Transportation Assets

Wael A. Zatar

Abstract

Federal and state transportation agencies across the world face a multitude of challenges to effectively maintain cost-effective core maintenance programs for managing a safe, yet sustainable transportation assets' program. The decision-making process involves several risk factors, and the prioritization of these factors could considerably affect both the level of utilization of these assets, as well as short- and long-term management protocols and plans for these agencies. The Moving Ahead for Progress in the 21st Century Act requires each state Department of Transportation in the United States to have a risk-based asset management plan in place to preserve the condition of their assets and improve the performance of the National Highway System. Many transportation agencies lack the financial and human resources to achieve their targets, and therefore they may opt to make trade-offs, lower targets, and perhaps drop some important objectives. Trade-off decisions can become clearer when objectives and targets are viewed through the lens of which options reduce the top-priority risks, such as reduced risk to safety, asset performance, or future costs. This chapter primarily focuses on emphasizing the importance of risk management in transportation networks and demonstrating the relationship between environmentally influenced risk management and sustainable management of state-controlled transportation assets in the United States. Several key parameters including risk assessment, financial risk and organizational behavior are addressed. Successful examples demonstrating how transportation agencies have identified how to best address a given risk, and in turn impact the resource allocation process are provided.

Keywords: state controlled transportation assets, environmentally influenced risk, risk assessment, financial risk, organizational behavior

1. Introduction

Federal and state transportation agencies in several countries face a multitude of challenges to routinely maintain effective and cost-effective core maintenance programs for their transportation assets. The focus on uncertainty and variability highlights the importance of managing both opportunities and threats to the agency's priorities. Risk management is a strategic approach that usually adapts to agencies' specific circumstances. It can primarily pave the road for better alignment between operations and the agencies' strategic objectives.

The Transportation Research Board's (TRB) National Cooperative Highway Research Program (NCHRP) Report 08–93 [1] lists levels of risk within transportation agencies including the enterprise, program, project and activity levels. Risk management heightens the identification of threats that could impede objectives, particularly threats to the public's safety and well-being. Seismic excitations, scour damage, frequent flooding, and increasing storm frequency and severity exhibit significant risks to agencies hoping to sustain high-risk assets and to meet their asset-condition targets. Benefits of risk management include the ability to think strategically, produce time savings, enhance the ability to manage uncertainties, shift from a reactive mode to a proactive mode, and make informed decisions.

2. Moving ahead for Progress in the 21st century act (MAP-21)

The Moving Ahead for Progress in the 21st Century Act (MAP-21), signed into law In the United States in July of 2012 [2]. It requires each state Department of Transportation (DOT) to have a risk-based asset management plan in place by 2015 to preserve the condition of their assets and improve the performance of the National Highway System. MAP-21 amended the 23 U.S. Code § 119 - National Highway Performance Program to require State Departments of Transportation (DOTs) to develop risk-based Transportation Asset Management Plans (TAMPs).

3. Transportation asset Management plans

The Federal Highway Administration (FHWA) produced several reports between 2012 and 2013 to detail the concepts and vision for risk-based transportation asset management plans [3–8]. FHWA adopted in 2017 a final TAMP rule that elaborates on the MAP-21 requirements. Both the statute and the FHWA rule identify the TAMP as a central part of the larger Federal performance management process [9]. The TAMP is one of a series of plans State DOTs are required to develop to achieve the Nation's transportation goals. State DOTs are tasked with the development of plans for highway safety, congestion and freight [9]. These plans will continue to influence and inform the larger transportation planning process and its products, Long-Range Statewide Transportation Plan (LRSTP), and Short-Term State Transportation Improvement Program (STIP). Looking at the current transportation funding environment, many transportation agencies lack the financial and human resources to achieve their targets. The agencies must make trade-offs, lower targets, and perhaps drop some important objectives. Trade-off decisions can become clearer when objectives and targets are viewed through the lens of which options reduce the top-priority risks, such as reduced risk to safety, asset performance, or future costs.

The objective of a risk based TAMP is not to avoid all risks. Rather, it is to acknowledge risks, assess and prioritize them, and allocate resources and actions based on the agency's risk tolerance and how the risks could affect the asset management objectives. Risk-based TAMPs acknowledge, identify, assess, and prioritize risks that affect performance. They should identify high-risk assets, such as structures prone to seismic waves, scour damage, frequent flooding and increasing storm frequency and severity [10]. Risk-based TAMPs help agencies make difficult trade-offs of scarce resources to address top-priority risks. By identifying risks, agencies can be more informed about managing their performance.

The FHWA finalized guidance documents for both Transportation Asset Management Plan Development Processes Certification and Recertification Guidance, and Transportation Asset Management Plan Consistency Determination Interim Guidance [11]. These documents were developed to provide implementation guidance on provisions of the MAP-21 and the Asset Management Final Rule, which requires a State department of transportation to develop and implement a risk-based asset management plan [11]. FHWA must certify that TAMP development processes established by a State DOT meet applicable requirements, and make an annual consistency determination, evaluating whether a State DOT has developed and implemented a State-approved TAMP that meets all applicable requirements [11].

4. TAMP goals and targets

TAMP managers and leads in transportation agencies are strong advocates who organize meetings, set schedules, and clearly articulate the group's objective. Their task focuses on identifying, analyzing, prioritizing, and describing how to manage risks to the agency's asset management objectives. It is always advantageous if the TAMP lead has no vested interest in the outcome of the exercise and can engage the entire group to think through the risk management process for all areas relating to the TAMP during the exercise. The type of data and information the group should compile include, but is not limited to: (a) asset management goals and targets; (b) the process for developing the goals and targets; (c) level of achievement of these goals and targets in the past; (d) level of matching with life-cycle planning; (e) checking if the goals and targets take into consideration the long-term effects and the desired State of Good Repair (SOGR); and (f) level of comfort of the staff about meeting these goals and targets [12].

5. Financial forecasting and planning

Transportation agencies perform financial forecasting to plan for future management of their infrastructure assets [13–15]. They examine: (a) types of revenues and bonds; (b) whether revenues are rising or falling; (c) duration and expiation of revenue sources; (d) new initiatives of expansion, safety or other agency high priorities that require funding and if they been considered in future projections; (e) fund availability for investing in assets; (f) level of confidence in the forecast; (g) past trend lines of asset conditions and the accompanying expenditures; and (h) whether the conditions trended positively or negatively, and how were those trends affected by programming decisions [16–19].

In addition, transportation agencies should gather information about major influences that will affect their TAMP and to examine if these agencies expect changes in population, traffic, contractor availability, climate, sea levels, or even revenues and appropriations, that could affect the TAMP. Moreover, the agencies consider the number of structurally deficient structures, aging assets, or deteriorated assets as these will significantly impact the financial planning. The financial planning's should incorporate sound key assumptions that are utilized in managing and forecasting bridges and pavements, as well as other asset investment needs [11–13]. Assumptions related to inflation rates, asset deterioration rates and material performance are included, and the level of accuracy or confidence in the forecasting models should be documented [11–13].

Studies or forecasts for environmental risks that could affect asset performance or agency costs and the likelihood and anticipated severity of seismic activity or extreme weather events should be examined. In accordance with the FHWA's Special Federal-Aid Funding—Implementation of 23 CFR Part 667: Periodic Evaluation of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events [20], agencies should examine if their inventories include assets from past events that need to be addressed because of environmental conditions such as excessive floods that have created ponding and expedited asset deterioration or fires that have destabilized slopes.

Transportation agencies implement methodologies to describe the process that is used to incorporate the results of the FHWA's 23 CFR Part 667 evaluation into risk management. Each agency should develop and implement an emergency event risk register and prioritize the risks and create risk scores. The development of a risk register assists with the risk management process. The likelihood of the development of environmentally impacted events should be taken into account when developing a risk register. The register could include should cover varying levels of risks ranging from very low to very high ones. Risk scores are essential for making solid decisions for the programming needed to better manage and maintain the agencies' assets.

The TRB NCHRP Synthesis Report on 556 [21]. The objective of this synthesis report was to document practices by state DOTs to identify locations where highway assets have been repeatedly damaged and to identify considerations for mitigating the risk of recurring damage in those areas. The synthesis report focuses on identifying decisions and practices that support use of the results to improve achievement of asset management or performance management objectives [21].

6. Measuring success and continuous improvement

FHWA produced a report for incorporating risk management into transportation asset management in 2017 that depicts a risk management process [9]. It exhibits an iterative monitoring and review process where transportation agencies monitor the risks and update the risk management documentation once these risks are identified, analyzed, and a mitigation plan is developed. The process is generally consistent with ISO Standard 31000, as well as FHWA's requirements for state DOTs to assess risks to the National Highway System (NHS) assets in developing a TAMP.

Successful integration of risk into asset management plans and processes revolves around several key elements and relying on a high-level (top-down) support because risk management works best when it supports executive decision making and developing a robust analysis that demonstrates the long-term consequences of investment scenarios. In addition, successful risk-based, asset management processes should address resiliency through an accurate prediction and mitigating of external environmental risks including storm events, seismic events, flooding, and other natural events and environmental impacts [20]. Few agencies started their risk efforts with sufficient talent and experience while others started their efforts by acquiring the human resources and receiving needed training. Transportation agencies should develop a plan for measuring their level of compliance and the resulting level of success meeting their goals and targets. Continuous improvement of risk management skills and processes is gaining more attention day after day [11, 12].

7. Risk-informed resource allocation of transportation agencies

Resource Allocation is a key component of Transportation Asset Management (TAM) [22]. This chapter primarily focuses on emphasizing the importance of risk management in transportation networks and demonstrating the relationship between environmentally influenced risk management and sustainable management of state-controlled transportation assets in the United States.

The American Association of State Highway and Transportation Officials (AASHTO) developed a transportation asset management guide that describes essential components for resource allocation and prioritization process, cross-asset resource allocation methods, TAM financial plans, and work planning and delivery. Chapter 5 of the AASHTO Guide describes the resource allocation process and provides guidance on implementing a resource allocation process that makes the best use of asset data and systems to allocate scarce resources in a timely manner in support of TAM-related goals and objectives [23].

The AASHTO Guide includes several examples where it specifically stated that an organization may identify through its risk management approach areas where better data or improved processes are needed to best address a given risk, in turn impacting the resource allocation process. For instance, if uncertainty concerning future asset conditions is found to be a significant risk, this may result in efforts to improve the deterioration models in an agency's asset management systems and/or motivate data collection improvements to reduce uncertainty.

8. Successful examples for risk-based asset Management of Transportation Infrastructure

Many transportation agencies lack the financial and human resources to achieve their targets for the maintenance of their transportation assets and have started employing risk management in the management of transportation networks. The TRB recently produced NCHRP 08–103 in 2020. The report includes case studies in cross-asset, multi-objective resource allocation [24]. In addition, several studies were successfully conducted in the past few years to better assess the risk associated with elevated environmental challenges on various transportation assets. Collaborating with several transportation agencies, the following examples highlight the author's efforts and success for employing risk management in the asset management of federally and state transportation networks.

The United States Army Corps of Engineers (USACE) has a large inventory of navigation locks and dams that use gates to control water flow. Monitoring and inspecting components of locks and dams, such as Milter/Tainter gates, are generally performed by visual inspection. The visual inspection relies heavily on subjective assessments made by inspectors and significantly differ from one expert to another. Structural health monitoring (SHM) can assist making accurate condition assessment of infrastructure assets to perform their intended design function(s), based on sensor and inspection data, numerical engineering models, and statistical analyses.

SHM principles and technology provide continuous information to support maintenance, operation, and repair decisions. Though automated SHM systems are gaining acceptance, they have been applied in an ad-hoc manner to monitor navigation locks and dams. SHM uses dense sensor suites, which are designed to catch unforeseen events rather than being optimally designed to provide specific information.

Zatar et al. [25] carried out an extensive study that aimed at performing critical reviews of the effectiveness of SHM systems that have recently been employed for a few of the United States Army Corps of Engineers navigation locks and dams. **Figure 1** shows the vertically framed gates of the Miter dam and **Figure 2** shows a typical flow-chart for data analysis of dam structural health monitoring that is used for the Miter dam. The physical SHM system, sensing suite, data acquisition hardware, telemetry, and data anomalies are discussed and recommendations for improved SHM systems for the United States Army Corps of Engineers navigation locks and dams are provided.

Mid-Atlantic Transportation Sustainability University Transportation Center (MATS UTC) served as focal point in Region 3 of the United States Department of Transportation. The MATS UTC includes the District of Columbia (Washington D.C.) and five states including Delaware, Maryland, Pennsylvania, Virginia, and West Virginia. Transportation infrastructure in this region, particularly concrete highway bridges, are exposed to the deleterious effects of environmental attacks, leading to environmental degradation of the concrete materials [26]. This is due to, for example, carbonation and chloride contamination that eventually break the alkali barrier in the cement matrix, and the steel reinforcement in the concrete becomes susceptible to corrosion. As a consequence, the concrete deteriorates at the reinforcement level, leading to cracking and spalling of the concrete owing to volume increase of the steel reinforcement. Such degradation is exacerbated by the application of de-icing salts on highway bridges, and the freeze–thaw and dry-wet cyclic exposures causing accelerated aging of the structure over time.

Concrete deterioration in the United States and worldwide has motivated the development of new and innovative materials and methods for structural rehabilitation, since replacement of structures would be very costly and nearly prohibited [26]. FRP composite materials in the form of fabrics, laminates, and bars have been externally bonded to concrete structures to increase structural capacity and provide longer service-life. The goal of this project was to present the technical and economical effectiveness of externally bonded FRP composites for repair and retrofit of highway infrastructure, and particularly concrete bridges [26]. The application of this technology in practice has been highly successful in West Virginia (**Figure 3**).

Composite behavior of precast Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) slabs connected to Fiber-Reinforced Polymer (FRP) I-shaped girders was examined as a potential sustainable and low-cost maintenance alternative for composite bridge construction. Two series of large-scale FRP-UHPFRC composite girders were tested monotonically under four-point

Figure 1.
Vertically framed Miter dam.

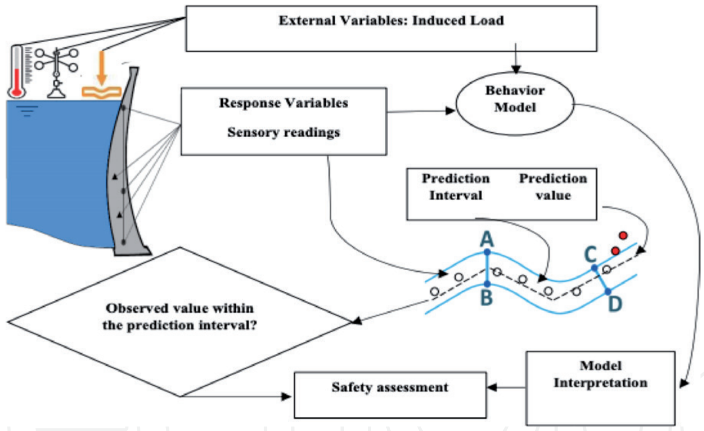

Figure 2.
Typical flow-chart for data analysis of dam structural health monitoring.

Figure 3.
Degradation and retrofitting of highway bridges in West Virginia. (a) Spalling of concrete and exposed rebars of bridge superstructures (curtesy of WVDOT–WVDOH); (b) retrofitting of highway bridge wing walls using GFRP wraps (curtesy of WVDOT–WVDOH).

flexural loading [27]. The test results showed promising indicators for short-span and pedestrian bridges. The developed girders were successfully employed in the construction of two demonstration pedestrian bridges in Japan. The established technology exhibited a sustainable and fast bridge construction solution in harsh environments [28].

The Region of Peel in Ontario, Canada, assesses needs and priorities across a diverse portfolio of Infrastructure that supports a variety of programs and services. These programs include solid waste management, water and wastewater treatment distribution, roadway network, and a variety of social, health and emergency services. The Region successfully integrated several efforts to enable an optimized investment methodology. The Region accounted for risk management, level of service, and life cycle management strategies to prioritize needs across its diverse infrastructure system [29].

The approach for allocating funding within the Caltrans State Highway Operation and Protection Program (SHOPP) in the State of California is a great example of a multi-objective, cross-asset resource allocation approach. SHOPP funds are used for repair, preservation, and safety improvements on the California State Highway System. The SHOPP programming cycle results in a multi-year program of capital projects that achieve the performance targets specified in the TAMP [24].

Other examples for successful transportation asset management efforts include: (a) Caltrans great example for TAMP-Practical Lessons from the Loma Prieta

Earthquake where the agency defined a separate program for seismic retrofits [30]; and (b) The Sustainable Solutions Lab at the University of Massachusetts Boston used a scenario-based approach to analyze the feasibility and potential risk reduction of Boston Harbor barrier systems to protect the Boston area from future flooding due to sea level rise [31].

9. Successful examples for risk-based TAMP in the state of West Virginia

9.1 Condition assessment of ground-mount cantilever highway weathering-steel overhead sign structures

Weathering steel (WS) is a high-strength, low-alloy steel and best known under the trademark COR-TEN or Corten steel. There are approximately 100 WS bridges and numerous WS overhead sign structures (WSOSSs) throughout the State of West Virginia, and inspection of these WS structures is essential to maintain public safety. Zatar and Nguyen conducted an expansive work that aimed at assessing 82 WSOSSs in the Charleston Interstate System in West Virginia [32]. A total of 26 comprehensive inspection forms were developed to objectively evaluate the current condition of 11 general types of sign structures. This part of the project focused on analyzing 25 single-armed and double-armed ground-mount cantilever WSOSSs (GMC-WSOSSs). **Figure 4** shows the locations of the overhead sign structures along I-64, I-79 and I-77 in Charleston, West Virginia.

A reliable ultrasonic testing technique was used to examine key components of the sign structures while the other components were inspected by visual inspection technique [33]. A rating methodology was developed to evaluate the sign structures at both the element level and their overall condition. The element condition was rated based on the developed rating criteria and score. The overall condition of each sign structure was then evaluated by the ratio between the total score of each structure and its maximum possible total score. It was concluded that all the GMC-WSOSSs performed relatively well after more than 40 years of service and exposure to moist weather condition of Kanawha County (climate zone 4A). The study found out that 52 percent of sign structures were found to be in fair condition and 48 percent were in good condition [33]. The rating system assisted the West Virginia Department of Transportation in making rational decisions about whether there is a need to repair or replace at-risk elements, connections, of these sign structures.

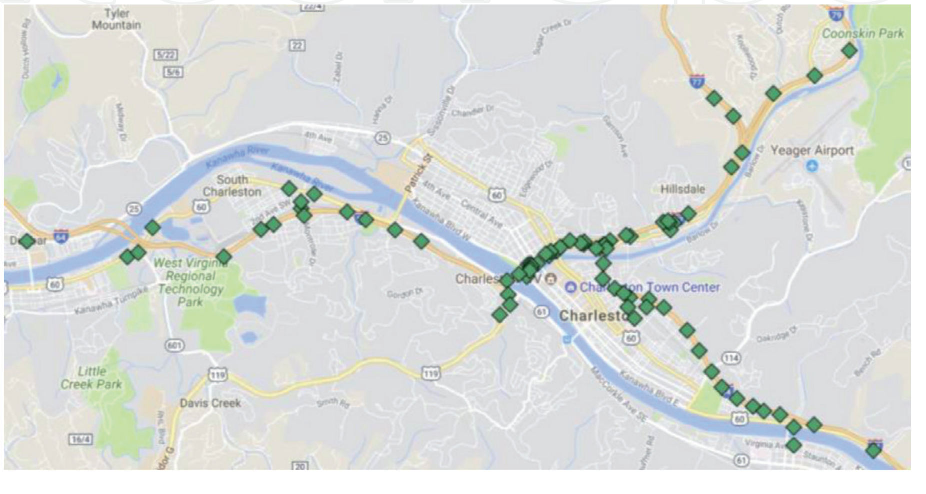

Figure 4.
Weathering-steel highway overhead sign structures along I-64, I-79 and I-77 in Charleston, West Virginia.

9.2 Performance of dual-shoulder-mount-truss highway weathering-steel overhead sign structures

Zatar and Nguyen conducted a study that focused on evaluating 15 dual-shoulder-mount-truss weathering steel overhead sign structures (DSMT-WSOSSs) in Charleston Interstate System in West Virginia [34]. A non-destructive testing technique was used to examine key components of the sign structures while the other components were inspected by visual inspection. **Figure 5** shows one of the dual-shoulder-mount-truss overhead sign structures. A rating methodology was developed to evaluate the sign structures at both the element level and overall condition. The element condition was rated based on developed rating criteria and score. The rating system assisted the West Virginia Department of Transportation in making rational decisions about whether there is a need to repair or replace at-risk elements, connections, or structures. All the DSMT-WSOSSs performed relatively well after four decades of service and exposure to moist weather condition of Kanawha County. Eighty seven percent of the sign structures are in fair condition and thirteen percent are in good condition [34].

9.3 Risk Management and rehabilitation of transportation infrastructure with FRP wraps

Concrete highway bridges in the State of West Virginia are exposed to the deleterious effects of environmental attacks, leading to degradation of these bridges as they age. The concrete deteriorates at the reinforcement level, leading to cracking and spalling of the concrete owing to volume increase of the steel reinforcement. According to 2017 National Bridge Inventory (NBI) database [9], West Virginia has 7,228 highway bridges and 19 percent of these bridges (1,372 bridges) were rated as structurally deficient. Of all the highway bridges in West Virginia, 1,394 bridges (19.3 percent) were rated as functional obsolete.

One solution to overcome steel corrosion in concrete for new construction is to use Fiber-Reinforced Polymer (FRP) materials for internal reinforcements instead of steel reinforcement. More significant is the beneficial application of FRP for structural rehabilitation of deteriorated concrete bridge structures. FRP composite materials in the form of fabrics, laminates, and bars have been externally bonded to concrete structures to increase structural capacity and provide longer service-life [26]. The application of this technology in practice has been highly successful [26].

Figure 5.
Dual-shoulder-mount-truss weathering-steel overhead sign structures.

Overall condition of all highway bridges in the State of West Virginia are reported where the data is extracted from the latest National Bridge Inventory by U.S. Department of Transportation and Federal Highway Administration. A few case studies for the use of FRP composites for rehabilitating bridge structures in West Virginia were examined. **Figure 6** shows two bridges in the inventory of West Virginia Department of Transportation. Cost of FRP-wrap projects by West Virginia Department of Transportation is addressed [35].

9.4 Non-destructive evaluation for risk and asset Management of Bridges

This project aimed at evaluating reinforced concrete bridge elements using two non-destructive evaluation (NDE) techniques, namely ultrasonic pitch and catch (UPC) and ground-penetrating radar (GPR). State-of-the-art literature reviews on multiple cutting-edge NDE techniques were carried out to identify potential knowledge gaps. **Figure 7** shows the basic principles of the UPC technique.

A validation test for a reinforced concrete slab specimen with embedded steel rebars and wire meshes was conducted to identify the advantages and limitations associated with the UPC and GPR techniques. **Figure 8** shows 3D visualization of the test specimen using NDT/NDE GPR and UPC (MIRA). **Figure 9** shows two-dimensional reconstructed image at an artificial delamination location. The high-resolution electromagnetic GPR technique accurately located almost all embedded reinforcements in the 3D slab volume tested.

The UPC technique detected rebars with large diameters while small diameter rebars and wire meshes could not be accurately detected. However, unlike the image obtained from the GPR data, 3D visualization reconstructed from the UPC's data showed very strong reflections of the slab bottom. The UPC technique usually requires multiple-point scanning for the targeted survey areas, resulting in a time-consuming data collection and processing. The research team recommended the combined use of the GPR and UPC techniques to comprehensively assess RC bridge elements, where the GPR is used to quickly evaluate questionable/defected regions while the UPC technique is used for an in-depth inspection/evaluation.

9.5 Evaluation of corrosion-induced risk and deterioration of concrete slabs using ground-penetrating radar and ultrasonic pitch-catch techniques

This project aims at evaluating corrosion-induced deterioration of RC bridge deck slabs using two non-destructive evaluation techniques, UPC and GPR. Experimental testing on RC slab specimens with pre-planned artificial defects was conducted to

Figure 6.
Two bridges in West Virginia Department of Transportation's inventory. (a) East Street Viaduct Bridge (curtesy of WVDOT - WVDOH bridge inspection reports 2012 and 2017); (b) Flag Run Bridge (curtesy of WVDOT - WVDOH bridge inspection reports 2016).

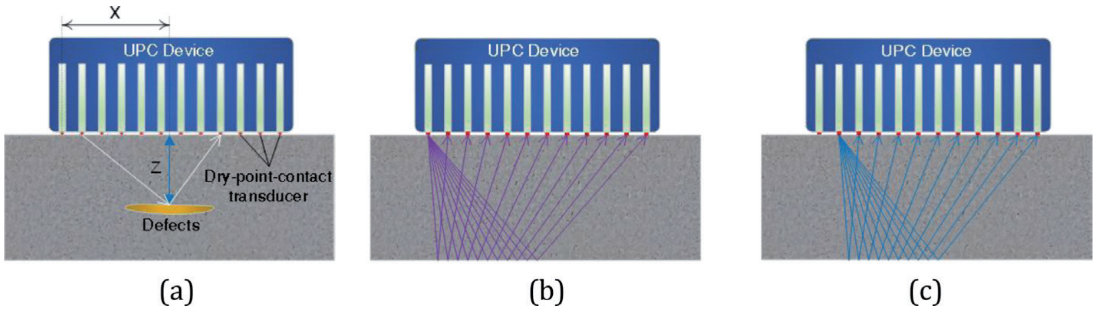

Figure 7.
Basic principles of the UPC technique: (a) transmitting and receiving transducers in UPC configuration; (b) the first channel transmit signals and the other channels receive the signals; and (c) the second channel transmit signals and the other channels receive the signals.

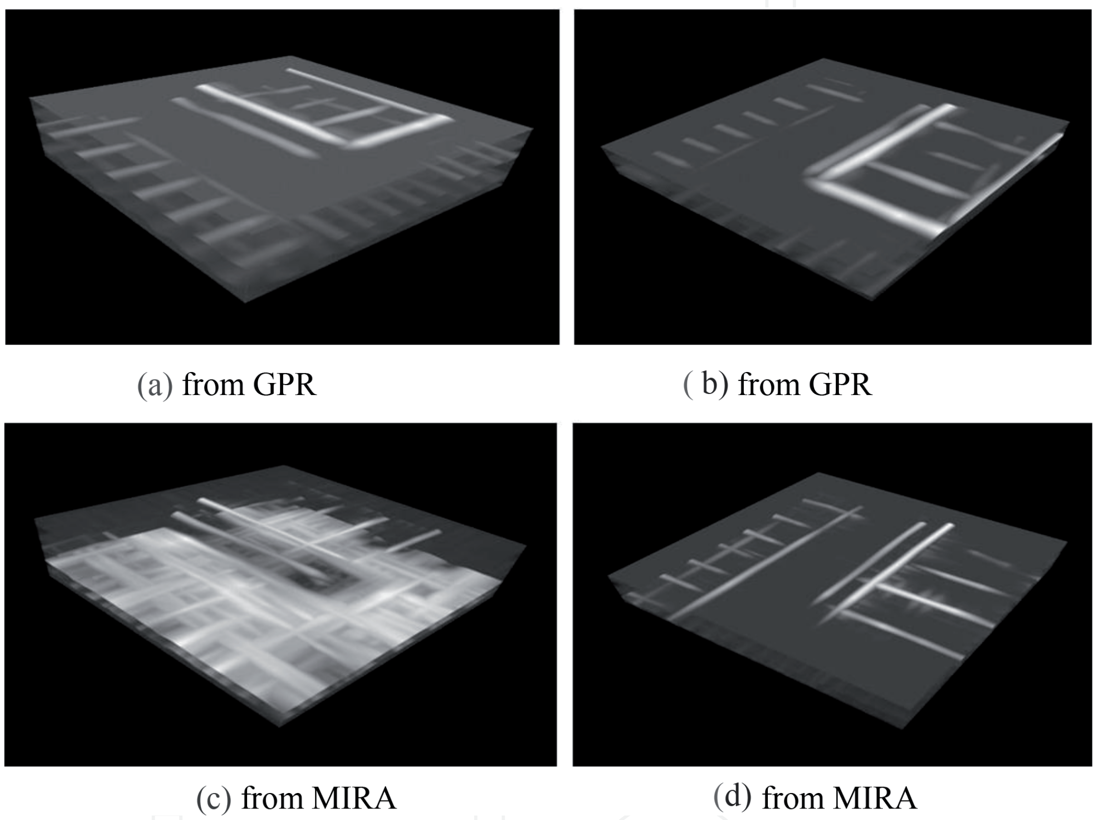

Figure 8.
3D visualization of the test specimen using NDT/NDE GPR and MIRA.

understand merits and disadvantages of each NDE technique. **Figure 10** illustrates the points at which data was collected for the RC slab using the UPC technique. **Figure 11** shows the signal amplitude versus depth of the delamination. The collected NDE data were used to generate both 2D and 3D images of layouts of reinforcements in the RC slabs [36]. The GPR effectively identified corrosion.

Potential areas of defects were generated using B-scan data. NDE data fusion approach was used to interpret the NDE data and to reconstruct the 2D/3D images. The GPR technique is not likely to be detect corrosion-induced concrete delamination. On the other hand, the UPC technique was found to be quite effective in determining and locating delamination, voids, reinforcing rebars, and pre-stressing tendons in the RC slabs. Major limitation of this technique is its sensitivity to the electrical properties of concrete such as the resistivity and dielectric constants. Therefore, the UPC is not suitable for detecting early signs of reinforcing bars corrosion. In addition, it requires a substantial amount of time to complete data

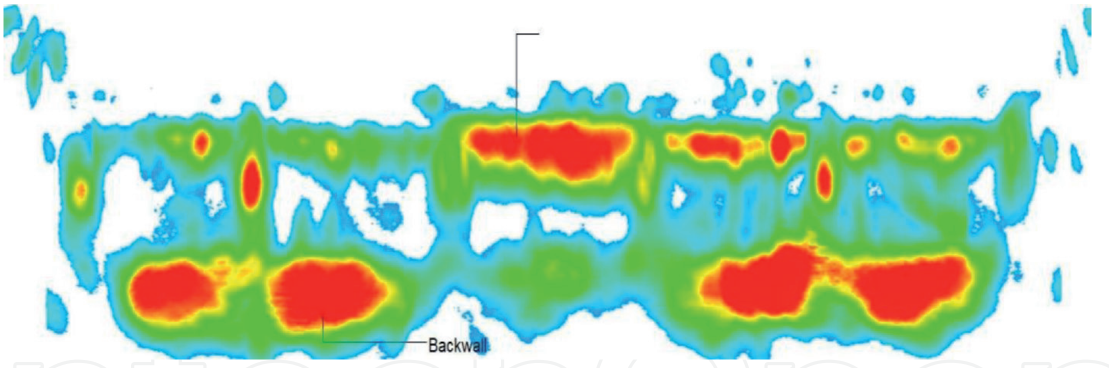

Figure 9.
Two-dimensional reconstructed image at an artificial delamination location.

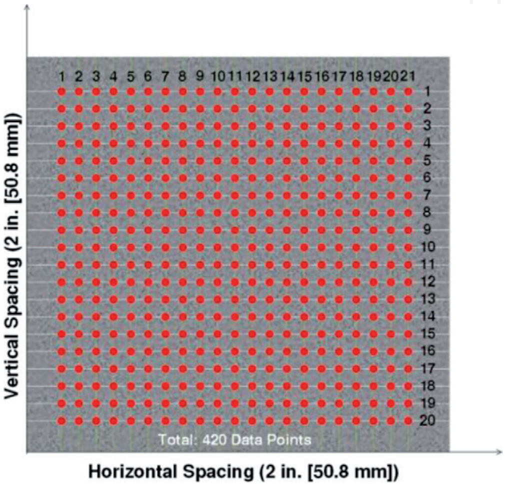

Figure 10.
Data collection on the RC slab using the UPC technique.

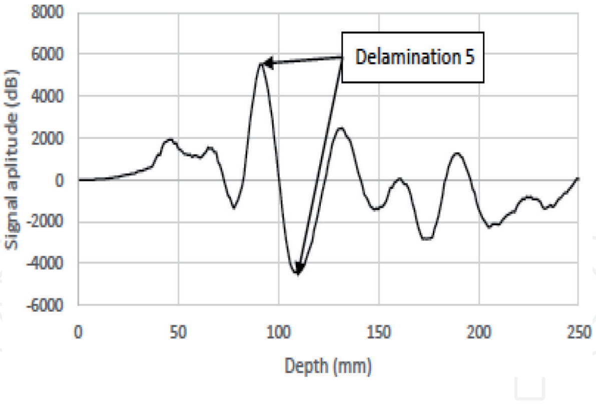

Figure 11.
Signal amplitude versus depth of the delamination.

collection. The GPR technique rapidly detected the highly corrosive regions in RC structures while the UPC technique can be used for in-depth evaluation and inspection of likely active corroding areas found by the GPR technique.

The project team recommended the combined use of GPR and UPC techniques for comprehensive assessment of corrosion-deteriorated bridge deck slabs [36].

9.6 Asset evaluation of concrete bridge deck slabs rehabilitated with composite Fiber-reinforced polymers

Fiber-reinforced polymer (FRP) materials have been widely accepted as an effective method in retrofitting deteriorated infrastructure (in shear, flexure and confinement applications). Despite the fast-growing and advanced technology in FRP materials and strengthening techniques, the monitoring and quality control of the FRP construction and installation remain challenging. For externally FRP-rehabilitated newly constructed and existing structures, it is critical to evaluate the potential for debonding failure and defects including cracks and voids surface on the concrete surface.

Accurate detection and evaluation of these defects is important to verify the structural capacity and to ensure appropriate durability of the FRP-strengthened structures. Experimental and theoretical non-destructive studies were conducted for concrete bridge deck slabs externally bonded with glass FRP, carbon FRP, and the combination thereof. **Figure 12** shows a sample reinforced concrete bridge deck slab specimen. Ground-penetrating radar (GPR) and infrared tomography (IRT) methods were utilized.

The results showed that the in-house developed software using an enhanced image reconstruction technique could provide high-resolution images of the FRP-strengthened reinforced concrete slabs in comparison to those obtained from the device's original software [37].

Figure 13 shows reconstructed images of the sample bridge deck slab specimen. The results obtained from the IRT camera indicated that this technology could accurately detect and locate near-surface defects such as debonding, cracks and voids. The study suggests that the combination of the GPR and IRT methods is effective in imaging internal defects of FRP-strengthened concrete structures.

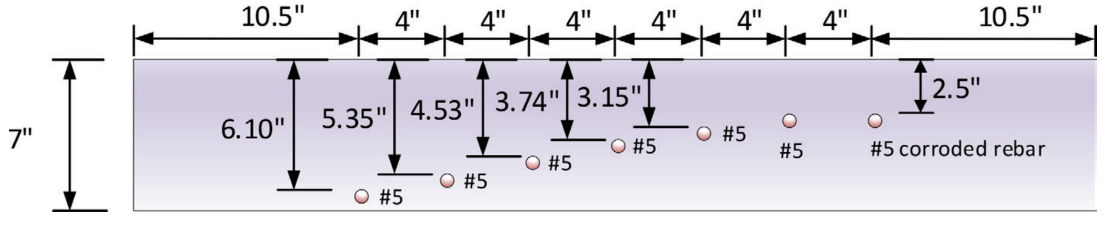

Figure 12.
Details of a sample reinforced concrete bridge deck slab specimen.

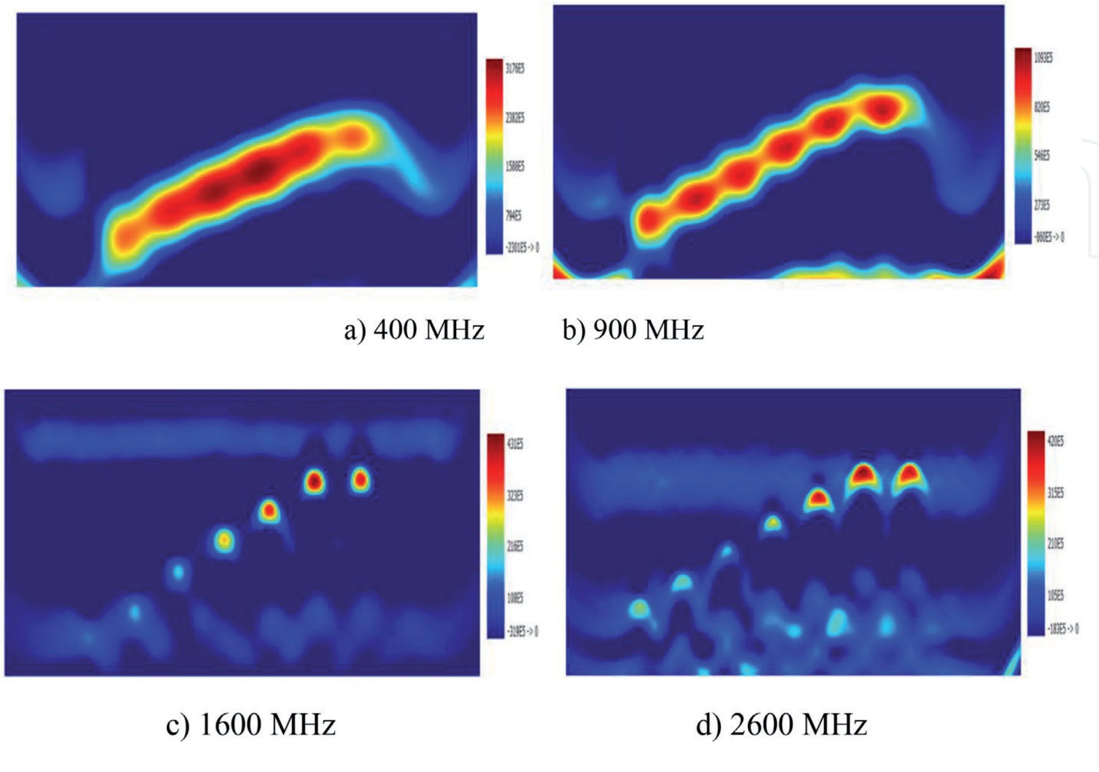

Figure 13.
Reconstructed images of the sample bridge deck slab specimen.

10. Conclusions and future works

Federal and state transportation agencies across the world are tasked with a multitude of challenges associated with routine, yet effective, maintenance and upgrade programs for the agencies' aging transportation assets. Challenging environmental conditions play a significant role in exacerbation the degradation, lowering the level of service, and increasing the risk of managing transportation agencies infrastructure assets. This is all happening at a time when limited funds are directed to sustain and enhance critical transportation assets. The chapter addresses the necessity to building and maintaining safe and sustainable transportation network for future generations, as well as highlights the implication of implementing life cycle cost measures to the process—as these measures add another level of complexity to the already difficult challenges facing transportation asset managers and decision makers.

The chapter stressed that the decision-making process involves several risk factors, and displayed the considerable effect of prioritizing these factors for both the level of utilization of these assets, as well as the short- and long-term management protocols and plans for transportation agencies. The relationship between environmentally influenced risk management and sustainable management of state-controlled transportation assets in the United States is demonstrated. Several key parameters including risk assessment, financial risks and organizational behavior are addressed, and multiple successful examples for risk-based transportation asset management in the State of West Virginia are highlighted.

Acknowledgements

The author would like to acknowledge the financial support and technical guidance provided by the West Virginia Department of Transportation–Division of Highways (WVDOH) while conducting several of the highlighted research studies.

The author would also like to acknowledge the diligent support provided by the research team members of the Encova Center for Engineering and Safety at Marshall University. The author would like to extend special thanks to Dr. Haroon Malik, Dr. Hai Nguyen, Dr. Hien Nghiem, Dr. Cumhur Cosgun, Dr. Tu Nguyen, and Dr. Kien Dinh for all their tireless efforts while conducting several of the studies highlighted herein.

The author would like to acknowledge the financial support provided through both the United States Army Engineer Research and Development Center and the Mid-Atlantic Transportation Sustainability Center University Transportation Center (MATS UTC). The successful collaboration and technical support provided by Dr. Osman Ozbulut from the University of Virginia, while conducting two of the highlighted research projects, are greatly appreciated.

Conflict of interest

The author hereby declares no potential conflict of interest with respect to the research of this article.

Author details

Wael A. Zatar
College of Information Technology and Engineering, Marshall University, Huntington, WV, USA

*Address all correspondence to: zatar@marshall.edu

References

[1] Proctor, G., Varma, S., and Roorda, J., "Managing Risk across the Enterprise: A Guide for State Departments of Transportation," National Cooperative Highway Research Program (NCHRP) Report 08-93, 2016. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP08-93_FullGuide.pdf

[2] MAP-21, the Moving Ahead for Progress in the 21st Century Act (P.L. 112-141), Federal Highway Administration (FHWA). https://www.fhwa.dot.gov/map21/#:~:text=MAP%2D21%2C%20the%20Moving%20Ahead,highway%20authorization%20enacted%20since%202005

[3] Risk-Based Transportation Asset Management: Evaluating Threats, Capitalizing on Opportunities, Report 1: Overview of Risk Management, Federal Highway Administration (FHWA) publications, 2012.

[4] Risk-Based Asset Management: Examining Risk-based Approaches to Transportation Asset Management, Report 2: Managing Asset Risks at Multiple Levels in a Transportation Agency, Federal Highway Administration (FHWA) publications, 2012.

[5] Risk-Based Transportation Asset Management: Achieving Policy Objectives by Managing Risks Report 3: Risks to Asset Management Policies, Federal Highway Administration (FHWA) publications, 2012.

[6] Risk-Based Transportation Asset Management: Managing Risks to Networks, Corridors, and Critical Structures Report 4: Managing Risks to Critical Assets, Federal Highway Administration (FHWA) publications, 2013.

[7] Risk-Based Transportation Asset Management: Building Resilience into Transportation Assets Report 5: Managing External Threats Through Risk Based Asset Management, Federal Highway Administration (FHWA) publications, 2013.

[8] Managing Risks and Using Metrics in Transportation Asset Management Financial Plans, FHWAHIF-15-020, Aug. 2015, accessible at https://www.fhwa.dot.gov/asset/plans/financial/hif15020.pdf.

[9] Incorporating Risk management Into Transportation Asset Management Plans, Federal Highway Administration (FHWA) publications, November 2017. https://www.fhwa.dot.gov/asset/pubs/incorporating_rm.pdf

[10] Integrating Extreme Weather into Transportation Asset Management Plans, an NCHRP 25-25 project, Sept. 21, 2015, accessible at https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=3723

[11] Transportation Asset Management Plan Development Processes Certification and Recertification Guidance; Transportation Asset Management Plan Consistency Determination Interim Guidance, A Notice by the Federal Highway Administration, Feb. 2018. https://www.federalregister.gov/documents/2018/02/22/2018-03618/transportation-asset-management-plan-development-processes-certification-and-recertification

[12] Using a Life Cycle Planning process to Support Asset Management, Federal Highway Administration Office of Asset Management, US Department of Transportation, November 2017. https://www.fhwa.dot.gov/asset/pubs/life_cycle_planning.pdf

[13] Proctor, G., and Varma, S., "Financial Planning for Transportation

Asset Management," Federal Highway Administration, 2015.

[14] National Highway Institute (NHI) Course on Financial Planning for Transportation Asset Management, Federal Highway Administration, Course Number FHWA-NHI-136002, 2019.

[15] Guidebook on Risk Analysis Tools and Management Practices to Control Transportation Project Costs, National Cooperative Highway Research Program (NCHRP) 08-60, Transportation Research Board, 2010.

[16] Work Planning and Delivery - A Guidebook for the Evaluation of Project Delivery Methods, Transit Cooperative Research Program (TCRP) Report 131, Transportation Research Board, 2016.

[17] Accelerating Transportation Project and Program Delivery: Conception to Completion, National Cooperative Highway Research Program (NCHRP) Report 662, Transportation Research Board B, 2016

[18] Alternative Technical Concepts for Contract Delivery Methods, National Cooperative Highway Research Program (NCHRP) Synthesis 455, Transportation Research Board, 2018.

[19] Construction Manager-at-Risk Project Delivery for Highway Programs, National Cooperative Highway Research Program (NCHRP) Synthesis 402, Transportation Research Board, 2010.

[20] FHWA's Special Federal-Aid Funding—Implementation of 23 CFR Part 667: Periodic Evaluation of Facilities Repeatedly Requiring Repair and Reconstruction Due to Emergency Events, 2017. https://www.govinfo.gov/content/pkg/CFR-2017-title23-vol1/xml/CFR-2017-title23-vol1-part667.xml

[21] National Cooperative Highway Research Program (NCHRP) Synthesis Report 556: Asset Management Approaches to Identifying and Evaluating Assets Damaged Due to Emergency Events, Transportation Research Board, 128 pages, 2020, DOI: https://doi.org/10.17226/25825.

[22] Transportation Asset Management (TAM) Guide, The American Association of State Highway and Transportation Officials, AASHTO 2020.

[23] The American Association of State Highway and Transportation Officials (AASHTO) Guide for Enterprise Risk Management—Chapter 5 Resource Allocation, First Edition, AASHTO 2016, available as an electronic document from the AASHTO Bookstore.

[24] National Cooperative Highway Research Program (NCHRP) 08-103: Case Studies in Cross-Asset, Multi-Objective Resource Allocation, Transportation Research Board, 2020, DOI: 10.17226/25684.

[25] Zatar, W., Haroon, M. and Nguyen, H., "Critical Review of Conventional Large Sensor Suites for Health Monitoring of Large Structures," Technical Report, U.S. Army Corps of Engineer, United States Army Engineer Research and Development Center, W912HZ-17-SOI-0031, 608 pages, 2020.

[26] Zatar, W., Nguyen, H. and Ozbulut, O., "Fiber-Reinforced Plastic (FRP) Wraps for Next Generation Sustainable and Cost-Effective Rehabilitation of Coastal Transportation Infrastructure in the Mid-Atlantic Region," Mid-Atlantic Transportation Sustainability Center University Transportation Center (MATS UTC), March 2018.

[27] Nguyen, H., Mutsuyoshi, H. and Zatar, W., "Hybrid FRP-UHPFRC Composite Girders: Part 1– Experimental and Numerical Approach," Journal of Composite

Structures, Elsevier, Vol. 125, pp.631-652, 2015.

[28] Nguyen, H., Zatar, W. and Mutsuyoshi, H., "Hybrid FRP-UHPFRC Composite Girders: Part 2–Analytical Approach," Journal of Composite Structures, Elsevier, Vol. 125, pp.653-671.

[29] Peel Enterprise Asset Management Plan, 2019, pp.141.

[30] Caltrans TAMP-Practical Lessons from the Loma Prieta Earthquake, p.174-180, 2018. https://www.nap.edu/catalog/2269/practical-lessons-from-the-loma-prieta-earthquake

[31] Feasibility of Harbor-wide Barrier Systems Preliminary Analysis for Boston Harbor, Sustainable Solutions Lab, University of Massachusetts Boston, May 2018, PP.250, https://www.greenribboncommission.org/wp-content/uploads/2018/05/Feasibility-of-Harbor-wide-Barriers-Report.pdf

[32] Zatar, W. and Nguyen, H. Evaluation of Weathering steel Overhead Sign Structures in West Virginia. Marshall University, 2014.

[33] Zatar, W. and Nguyen, H. Condition Assessment of Ground-Mount Cantilever Weathering-Steel Overhead Sign Structures. Journal of Infrastructure Systems, 2017, 23(4), p. 05017005.

[34] Zatar, W. and Nguyen, H., "Performance of Dual-Shoulder-Mount-Truss Weathering-Steel Overhead Sign Structures in West Virginia," BIT 5th Annual World Congress of Smart Materials, Rome, Italy, 2019.

[35] Zatar, W. and Nguyen, H., "Rehabilitation of Transportation Infrastructure in West Virginia with FRP Wraps," 5th International Conference on Sustainable Construction Materials and Technologies (SCMT5), Kingston University, London, UK, July 2019.

[36] Zatar, W., Nguyen, H. and Nghiem, H., "Ground-Penetrating Radar Reconstructed Image for Identifying Steel Rebars and Artificial Defects in Concrete Structures," Journal of Nondestructive Testing and Evaluation, Submitted, October 2020.

[37] Zatar, W., Nguyen, H. and Nghiem, H., "Non-Destructive Evaluation of Reinforced-Concrete Slabs Rehabilitated with CFRP/GFRP," American Concrete Institute Fall Convention, Atlanta, accepted, 2021.