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# Risk and Resilience Analysis Tool for Infrastructure Asset Management

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16. Abstract
This project develops a comprehensive analytical framework for risk-based infrastructure asset management for both normal and extreme management conditions. We integrate analytical procedures for quantitative risk assessment, asset management, and economic impact analysis into a holistic methodological framework for comprehensive assessment of the benefit and cost of proposed infrastructure management strategies or scenarios. Moving beyond this, the framework incorporates the bidirectional impacts between asset maintenance (for normal aging and deterioration) and risk management against extreme conditions. The framework producing quantitative cost and risk measures is useful for addressing the high-level questions that agencies face in long-term planning and management decision making such as project prioritization, resilience planning, and capital planning. To illustrate the application, the framework is applied to a case study on the surface transportation system of the United States Virgin Islands considering flood risk. Finally, a scalable and customizable GIS-based web tool implementing the risk assessment methodology is developed incorporating real data for USVI and multiple future flood scenarios with sea level rise.

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# 1 Introduction

Transportation or Infrastructure Asset Management Infrastructure (TAM/IAM) is a strategic approach that transportation managers have increasingly utilized to oversee and logically plan infrastructure at a system level, with the goal of maintaining and improving all assets efficiently for the public over a long-term basis. Taking advantage of technologically enhanced data collection and analysis abilities, state and local agencies have sought to integrate an increasing amount of information across many sources and asset types (Office of Asset Management [OAM], 1999, p. 6). In this effort, one aspect of asset management that has often been neglected- or at least not quantitatively considered- is comprehensive risk management on such a system level, involving planning for the uncertainty and variability of future major events on assets (OAM, 2013, p. 3). Natural hazards, such as tropical storm systems or flash flooding, pose threats to the safety and performance of infrastructure assets, affecting the safety and economy of the communities that rely on them. The increasing impacts of climate change mean that such threats are expected to be more frequent and severe in coming years, making effective risk-based TIAM and strategies to maintain resilient transportation systems even more important for system managers (OAM, 2013, p. 5).

Such a priority is recognized by the OAM within the U.S. Federal Highway Administration (FHWA), as well as many state Departments of Transportation (DOTs) and agencies. However, a more standardized, quantitative approach to risk- and resilience-based assessment and analysis at a system level is still needed to mesh with existing TIAM frameworks and decision-making processes. While TIAM emerged with a focus on integrated “universal” system management and long-term cost-effective performance, more frequent and severe threats to assets require planning for high-impact probabilistic events that cannot be precisely modeled (OAM, 1999, pp. 7-8; 2013, p. 5). As noted in a 2013 report from the OAM, previous planning under TIAM has often been based on gradual, predictable, and continuous changes in conditions and funding, largely drawing from past performance and experience. This neglects the significant impacts of severe events that are “erratic, abrupt, and almost always negative”, as well as their increasing likelihood and consequences (p. 1). Risk consequences can also contribute to faster-than-expected deterioration of assets across systems, meaning alterations in long-term models and planning are necessary, as we discuss later. Dealing with risks can pose a dilemma for managers already trying to allocate stretched resources and make informed investment decisions appropriately. We seek to address these challenges by developing our own framework for TIAM that integrates natural hazard risk analysis in a more standardized, quantitative methodology to produce cost-effective management strategies.

## 1.1 Relevant Infrastructure Risk and Resilience Studies

Approaches to evaluating, adapting to, and mitigating risks to assets across multi-modal transportation systems have been formulated in the past, though they each come with limitations due to scope of individual agencies and organizations. However, national groups such as the American Society of Mechanical Engineers (ASME) as well as the

FHWA have developed methodologies to guide the assessment and incorporation of general risk into asset management: ASME's Risk Analysis and Management for Critical Asset Protection (RAMCAP) Plus approach and the FHWA's Vulnerability Assessment (VA) framework (plus its associated Scoring Tool, VAST), which we explore in further detail later (Section 2.5). While they provide pertinent guidance, these broad frameworks require significant adaptation for application by managers, depending on the actual hazards, assets, and management processes in play; they are general sets of criteria and steps, in order to be flexible for varying uses.

Other existing frameworks have been highly specific instead, developed independently by individual agencies or in studies focusing on certain hazards or asset types. One such case was developed by the Colorado DOT in a 2016-17 study, the "I-70 Corridor Risk & Resilience Pilot", adapted from the RAMCAP Plus process to proactively inform agency decisions and resilience measures following major flood and rock fall events on Interstate 70 (Flannery, 2017, p. 1). Pairing assets and threats along the highway, the study examined hazards' effects on system robustness- asset performance, network redundancy, and post-event network resilience- and how risk, costs, and performance factor into one another, especially how costs of risk mitigation balance against costs of threat consequences for a return on investment (ROI) in a benefit-cost analysis (BCA) (p. 12; Kemp-Herrera, PowerPoint, 2018, pp. 2-3). After conducting its Interstate 70 pilot, a model for quantitative risk and resilience assessment is offered by the Colorado DOT, which developed a full framework, the 2020 "Risk and Resilience Analysis Procedure" for flooding, rockfall, and fire debris flow threats to roadways, bridges, culverts, and concrete structures.

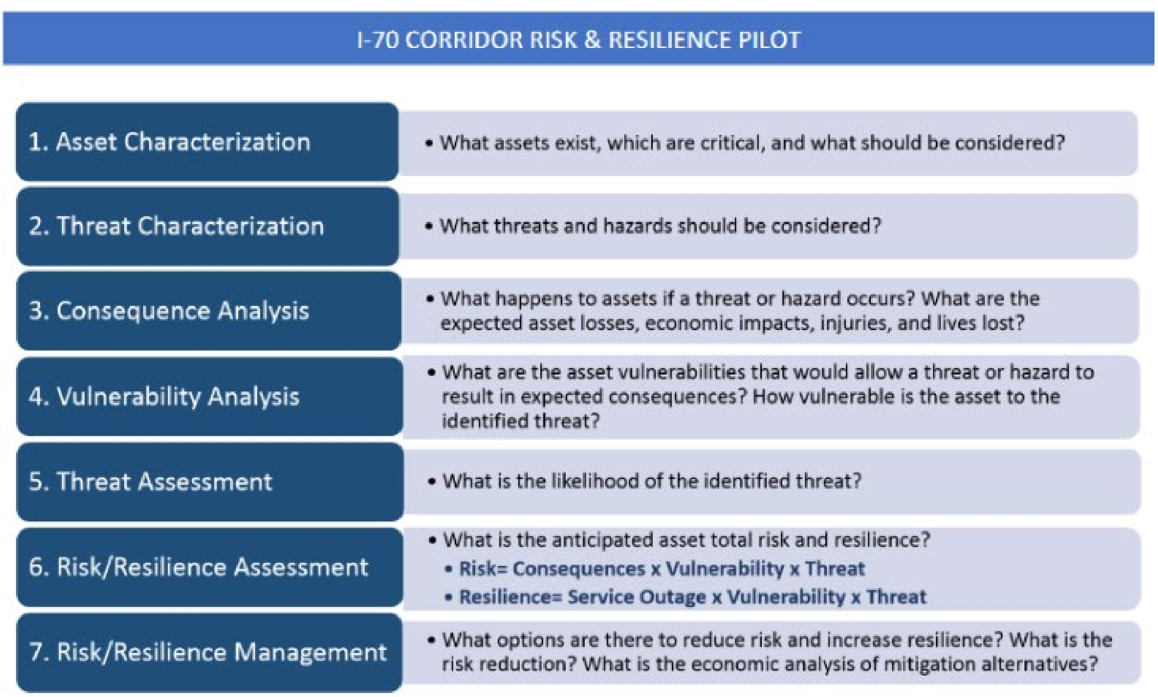



**Figure 1**: CDOT's R&R for Highways Process, based on RAMCAP Plus (Flannery, 2017, p. 6)

In addition, many agencies have also developed their own guidelines to ensure climate-resilient infrastructure moving forwards, such as the Port Authority of New York and New Jersey (PANYNJ) and its consideration of sea level rise (SLR) for coastal highway and bridge projects based on service life and how critical the asset is, requiring adjustments to project Design Flood Elevation (Port Authority, 2018, p. 6). Such cases are highly detailed and provide a comprehensive framework for the agencies that have developed and are using them, and they are easier to implement than the general frameworks offered by ASME and FHWA. However, they cover only certain types of assets and natural hazards, and can be highly localized.

More importantly, all these existing frameworks focus more on risk quantification and analysis than on risk management. How risk/resilience analysis can be utilized to factor directly into decision making, i.e., risk-based infrastructure asset management, is understudied in the literature. Based on our experience working with transportation agencies, a primary area that needs assistance in is determining optimal management strategies, including both capital investment and operational planning to minimize both the risk (i.e., expected cost) under extreme conditions and the life cycle cost under "normal" conditions. We summarized several questions that these agencies seek to answer, but which have not yet been addressed by a readily implementable framework: how can they identify and decide on cost-effective investment strategies for long-term infrastructure maintenance, considering their challenging fiscal situations, and how will they impact resilience in extreme conditions, broader economic growth, and long-term asset and system performance?

## 1.2 Study Scope and Approach Overview

Drawing from RAMCAP Plus, VA/VAST, and other past approaches, we develop a generic analytical framework for risk- and resilience-based TIAM for both normal and extreme conditions. We integrate risk assessment, asset management, and economic impact analysis (EIA) studying broader effects on user and agency savings and spending into a holistic methodological framework for comprehensive assessment of the benefit and cost of proposed infrastructure management strategies or scenarios. The framework is intended for addressing the high-level questions agencies face in decision making through project prioritization, optimization, and capital planning. The risk analysis component is based upon the Colorado DOT's procedure which involves the assessment of system asset inventory, asset criticality, risk type and likelihood, and asset conditions and vulnerability to particular risks (CDOT, 2020, p. 5). This combines the generality offered by RAMCAP Plus and VA/VAST with the level of detail employed by specific studies, establishing a readily implementable process for managers and DOTs. The resulting estimates of risk and its costs to owners and users can be factored into existing TIAM processes, including a more comprehensive asset life cycle cost analysis (LCCA), BCA, and EIA for risk mitigation and resilience measures. Moving beyond this, however, our comprehensive approach considers the bidirectional feedback between normal and extreme conditions. Subpar maintenance and investment in normal times can contribute to asset vulnerability and risk, producing subpar performance and resilience against threats in extreme conditions. On the other hand, hazard impacts contribute to worse-than-projected asset conditions, producing significant damage that must be considered for post-event asset and system resilience as well as new deterioration and maintenance modeling. Alternatively, proactive long-term maintenance may enhance performance and resilience against threats, while risk reduction investments can keep recovery and continued maintenance costs low in normal condition. Accounting for these risk drivers and impacts, the framework we present here integrates existing TIAM methodologies with risk analysis to produce quantitative outputs useful for planning decisions, such as costs and modeled performance of high-risk assets or LCCA/BCA for various system maintenance approaches, in a more standardized manner.

In this study, the risk-integrated analytical framework we constructed was applied to a case we conducted with the United States Virgin Islands (USVI) Territory and partner organizations, including University of Virgin Islands (UVI), Econsult Solutions, Inc. (ESI), and USVI Department of Public Works (DPW), focused on flood risk and the current surface transportation system of the Territory. The framework incorporates a wide variety of quantified factors, involving the identification of roadway and bridge inventory characteristics and their conditions, the analysis of flood risk and asset criticality, and the proposal of specific maintenance approaches and risk mitigation strategies across USVI's three main islands: St. Croix, St. John, and St. Thomas. The BCA and LCCA produced can help inform long-term management decisions with a comparative analysis of intervention scenarios generated, for both individual assets and the whole system. This study has culminated in the development of a customizable web-based, Geographic Information System (GIS) tool that implements our risk-integrated TIAM methodology, allowing DOT's and other agencies the ability to identify contributors and impacts of transportation asset risk and compare varying management approaches more easily.

Section 2 details our risk-integrated framework from initial inventory assessment to final decision-making and recommendations, breaking down each step and introducing methodologies and quantified factors. This begins with an overview of the questions addressed and the framework itself (2.1), followed by a description of asset characterization and criticality analysis (2.2) and establishment of possible agency strategies or scenarios for maintenance, recovery, and risk reduction (2.3). We then cover the assessment and quantification of asset conditions, performance measures and targets, and deterioration modeling results for LCCA by scenario (2.4), while introducing risk/resilience analysis and considering bidirectional feedback using RAMCAP Plus and VAST procedures (2.5). Lastly, we outline how EIA and BCA (2.6) are conducted to ultimately inform long-term investment decisions (2.7), based on economic or fiscal benefit to users, the agency, and the community. All of these steps are then applied to our USVI case study in section 3, using collected data (3.1) and intervention scenarios (3.2) for cost-effectively maintaining USVI's roadway and bridge network (e.g., rehabilitating and/or reconstructing road segments for varying thresholds of pavement condition ratings), with pavement and bridges across the territory encompassing the scope of the study. Following criticality analysis (3.1), intervention scenario and life cycle planning (LCP) modeling (3.3), and risk/resilience analysis for flood and storm surge (3.4), we conduct an EIA studying cost savings from maintenance by scenario, comparing costs of investment to costs of crashes (including injuries, fatalities, and damage to property) and vehicular wear and tear (3.5). While not entirely comprehensive, this case study analysis allows us to make recommendations given the financial feasibility of actually carrying out the proposed scenarios. We conclude with a summary of challenges, recommendations, and greater consequences at stake for the USVI and U.S. DOTs and transportation agencies considering risk-integrated TIAM on limited budgets, while introducing our interactive GIS-based web tool. (section 4).

# 2 Analytical Framework

Many transportation agencies face the challenge of determining the optimal level of investment (e.g., asset maintenance and treatment) over the infrastructure they manage. They hope to understand the economic value of current suboptimal versus adequate maintenance. Additionally, the following questions have been identified as important considerations faced by infrastructure owners when infrastructure planning decisions:

- How should maintenance funds be allocated given limited funding and the challenging fiscal situation?
- How would these decisions impact the infrastructure condition in the years to come and in the longer term?
- What are the interdependencies between the infrastructure system and its subsystems? What are the cascading impacts of failure in one component on others?
- What are the broader and long-term economic and fiscal impacts? What is the optimal investment level for infrastructure maintenance that will balance expenditures with economic growth?
- What is the role of infrastructure maintenance in risk reduction strategies? How will maintaining infrastructure regularly in normal conditions improve resilience in extreme situations?

## 2.1 Overview

In order to address the above questions, we develop a holistic analytical framework for providing quantitative solutions by integrating and perspectives of infrastructure asset management, risk and resilience, and economic impact analysis. Figure 2 presents an overview of the framework. The results of this framework will facilitate an understanding of the importance of transportation infrastructure and its management to the economy and help determine the level of investment that is warranted to optimize the infrastructure lifecycle.

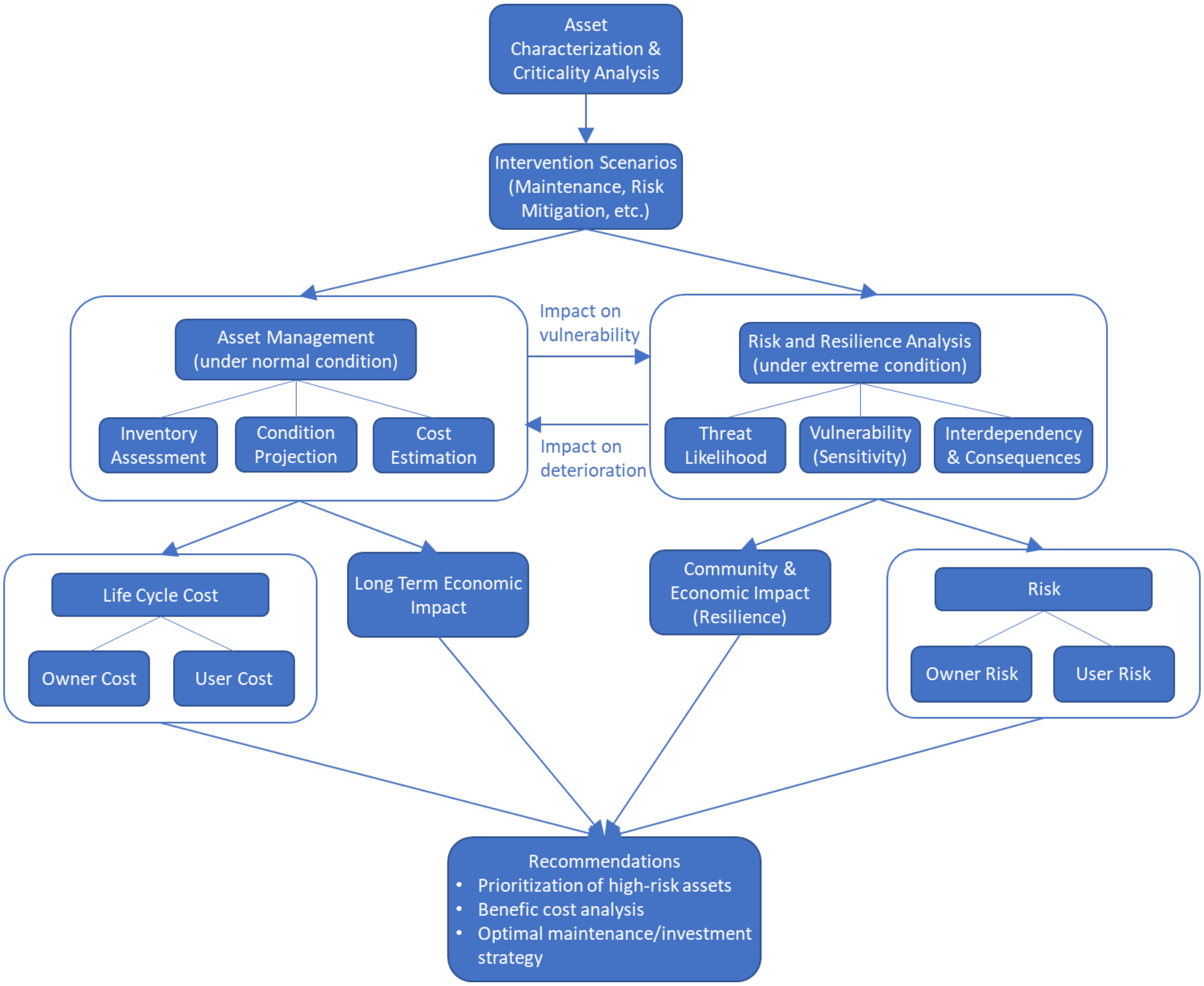



**Figure 2**: Our analytical framework visualized

To illustrate application of the analytical framework and methodology, we select two types of transportation infrastructure assets, roadway pavement and bridges, which have large impacts on a region's economy and daily life, as representative assets to develop our methodology and create several use-cases, which can be scaled up to the integral infrastructure system.

## 2.2 Asset Characterization

### Define Study Scope

This step is to define the study scope by identifying: 1) the type of infrastructure (that are highly impactful and potentially vulnerable to natural hazard events in the study area); and 2) the set of assets to study (that belong to certain categories, are within a geographical or jurisdictional boundary, or are on an important corridor). When resources are limited to perform the full-scale risk and resilience analysis for all the assets in the system, a criticality analysis can be conducted to prioritize those important assets that have potentially high risk or impact on the entire infrastructure system, the community, and the economy. In addition, data availability may be a key factor that limits which assets are included in the risk-based asset management (FHWA VAAF 2017). For example, an assessment often needs a variety of asset data, but only some of them may be readily available. For quantitative analysis, the agency may have to invest significant effort or resources to gather the necessary information and convert it into a usable format. Therefore, the study scope may also be limited to those assets with full sets of data readily available. Other factors such as the assets' geographical location, representativeness, stage of life may also be considered in selecting the assets for study.

### Criticality Analysis

Once assets have been identified, agencies determine each asset's criticality. Criticality does not measure the cost of an asset, nor the likelihood of an asset's failure under a hazard, but rather the significance of the asset to the overall system's resilience. The more critical an asset is for a system, the more successful it will be in delivering its service for its users. For instance, in our St. Thomas case study in Section 3.1, the more critical a road segment is to a user, the more important it is to be sufficiently resilient. In doing so, more lengthy detours or unsafe trips during and after flood events can be avoided, which in turn, makes it easier for users to traverse.

According to a methodology developed by Colorado DOT (CDOT, 2020), criticality is a measure of the importance of an asset to the overall highway system operations. Determining an asset's criticality level can be used in conjunction with an asset's vulnerability to determine its risk and resilience levels. In addition, the criticality analysis, in conjunction with condition assessment, life-cycle cost analysis (LCCA) and risk analysis, is also useful in determining management priorities, investment strategy, budget allocation among assets.

For highway transportation infrastructure, factors to determine criticality include: Usage (e.g., traffic), Classification (e.g., the American Association of State Highway and Transportation Officials (AASHTO) classification for roadway), Freight Value, Tourism Value, System Redundancy, Location (e.g., linkage to other critical infrastructure or on emergency evacuation routes), etc. Given the limited data that is available to the project team, we use AADT and AADTT to represent some of these criteria to perform a preliminary criticality analysis. The following criticality assessment table is listed as an example. Redundancy can be measured by the number of alternative routes available for travelers on, which is, however, sometimes hard to define or quantify, especially when the highway network is complex. Therefore, in this analysis, we use detour distance as another measure of redundancy for roadway assets, in the sense that the longer the detour, the less likely there are nearby alternative routes for a specific road segment. For bridges, we can use the number of alternative bridges to define the redundancy score. The categorization and scoring of these criteria need to be determined or validated by expert judgement. For example, for location factor, we categorize it in three criticality levels:

> High – if a road segment or bridge is within 1 mile to or the only way connecting to a critical infrastructure, facility or site, e.g., tourism site, emergency facility or evaluation routes, hospital, airport, utility facility, etc.
> Moderate – if a road segment or bridge is within 1 to 3 miles to or on one of the alternative routes connecting to a critical infrastructure, facility or site
> Low – if a road segment or bridge is more than 3 miles away and is not on the alternative routes connecting to a critical facility

Table 1 shows example criticality criteria for determining the criticality level of transportation infrastructure:

**Table 1**: Example of Transportation Infrastructure Criticality Criteria

| Criteria | Level | | |
|---|---|---|---|
| | Low<br>1 | Moderate<br>2 | High<br>3 |
| **AADT** | < 5,000 | 5,000 – 10,000 | > 10,000 |
| **AADTT** | < 1,000 | 1,000 – 2,000 | > 2,000 |
| **Redundancy (e.g., number of alternative routes or detour time)** | > 4 routes or<br>< 10 min | 3-4 routes or<br>10 min – 20 min | < 2 routes or<br>> 20 min |
| **Location (e.g., distance to nearby critical facilities)** | > 10 km | 5 – 10 km | 1 - 5 km |
| **Individual Score** | 1 | 2 | 3 |
| **Total Score** | **9-12** | **5-8** | **1-4** |

We will discuss in detail how we apply these guidelines to define the study scope and determine criticality in the case study and analysis in section 3.

## 2.3 Maintenance/Repair/Risk Mitigation Scenarios

In order to determine the optimal investment or management strategy, the ideal way is to quantitively evaluate and compare the benefits and costs of all alternative options in terms of life-cycle cost (LCC) and economic impact of the infrastructure under normal operating condition as well as risk and resilience under extreme condition. The investment levels or management strategies are expected to affect both the infrastructure's resilience response to natural events and the long-term performance of the infrastructure system. Therefore, it is essential to conduct the analyses under a specific investment or management strategy scenario to quantify the benefit of risk and LCC reduction, condition improvement, and the associated broader economic value.

This step is to identify a number of alternative scenarios of infrastructure maintenance, repair, rehabilitation and risk mitigations. A scenario can reflect the agency's general strategy or policy for how they plan intervention activities or react to the damage or deterioration condition of infrastructure. An infrastructure asset management scenario should regularly define the following three aspects for each of the assets in the study scope:

1) Type of action. It should include at least one type of action besides the do-nothing option. The type of actions could be either one or more main categories for strategic level analysis (e.g., maintenance, repair, rehabilitation) or specific treatment options within one or more main categories for detailed, fine resolution analysis (e.g., pavement patching, 2 inch or 4 inch overlay, etc.).
2) Timing of action. It should include when each action will be performed, based on either a fixed frequency or the condition (i.e., trigger point).
3) Applicable asset. This could be decision rules or policies applied to specific assets or categories of assets. For example, maintenance may be applied to major and minor roadway sections at different frequencies.

For example, for pavement, the state-of-practice of many state agencies follows a decision tree to select among a number of treatments the based on the condition rating, e.g., Pavement Condition Index (PCI). Table 2 and Figure 3 list examples of pavement treatment actions and a treatment decision tree.

**Table 2**: Sample Pavement Treatment Types Defined in Treatment Families

| Name | Description |
|---|---|
| **Do-Nothing** | Those pavement sections that do not have sufficient distress level to warrant expenditure of funds. |
| **Pavement Preservation**<br>Crack Sealing, Slurry Seal, Microsurfacing, Fog Seal, Chip Seal | Those pavement sections that require minimal treatments to seal the pavement surface to prevent moisture from entering the pavement structure. |
| **Minor Pavement Rehabilitation**<br>(Mill X/Pave X), Hot In-place Recycling, Thin Overlay<br>[Maintain Pavement Elevation] | Those pavement sections that require a functional overlay treatment to improve pavement ride quality, skid resistance, or rutting. |
| **Major Pavement Rehabilitation**<br>(Mill X/Pave X+), Cold In-place Recycling<br>[May increase Pavement Elevation] | Those pavement sections that require a structural overlay treatment to improve the pavement structure and pavement ride quality, skid resistance, or rutting. |
| **Reconstruction**<br>Partial, Full, Full Depth Reclamation | Those pavement sections that require a partial or complete reconstruction due to extensive pavement deterioration. |

The Treatment Selection Methodology is used to identify which pavement treatment family is appropriate on a given section based on pavement treatment decision trees, decision rules or PCI level.

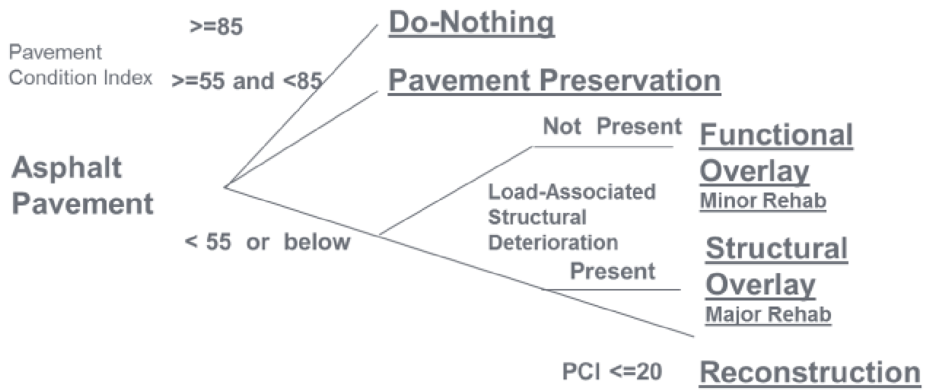



**Figure 3**: An example of pavement treatment decision trees

In the case of bridges, many agencies use NBI condition rating as criteria for determining preservation, repair, rehabilitation, and replacement actions. The following are two example scenarios for LCCA for a single bridge deck:

Scenario 1: no preservation, maintenance, or repair, only replace the deck when the NBI rating reaches 4
Scenario 2: perform preservation actions on bridge deck when the NBI rating reaches 7, and perform repair actions when the NBI rating reaches 5

For network-level analysis, budget needs to be considered. Example scenarios could be based on total budget or budget allocation among different actions.

In addition, if post-disaster repair or risk mitigation upgrade is concerned, the scenario should define the type and extent of repair or mitigation measures for each asset. For example, suppose we want to find out the optimal measures for reducing flooding risks of highway infrastructure, in addition to the benchmark do-nothing scenario, the alternative scenarios could be categorical such as

Scenario 1: Drainage improvement
Scenario 2: Road elevation

or specific actions, as detailed as the following examples in CDOT (2020):

Scenario 1 - Replacement of existing culverts with Two 72" concrete pipes with headwalls
Scenario 2 - Replacement of existing culverts with Two 8' x 8' CBC connected with a concrete chute and improvements to private crossing above interstate

## 2.4 Infrastructure Asset Management (Under Normal Condition)

To answer the strategic questions that are identified in the beginning of this report in a quantitative way, comprehensive infrastructure asset management analysis is needed. In general, it includes the following essential components in an integrated framework for a generic type of infrastructure: asset inventory & condition assessment, identification of performance target, deterioration modeling, life cycle cost analysis, and capital planning (Figure 4).

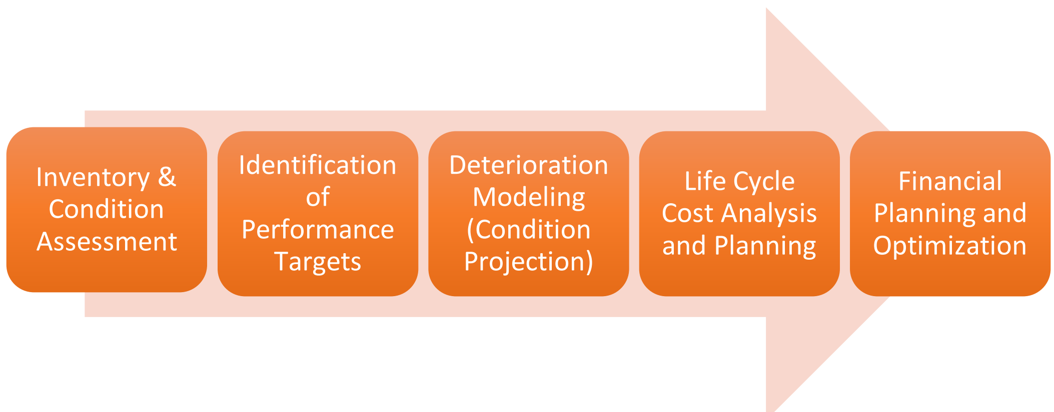



**Figure 4**: Components of a general infrastructure asset management framework

Infrastructure asset management is usually done through one or multiple asset management software systems, including both network and project levels analysis components. For example, for a pavement management system (PMS), the network-level PMS supported by the network-level data provides a broad overview of the inventory and condition of the agency's pavement network. A PMS is designed to provide objective information and useful data for analysis so that road managers can make more consistent, cost-effective, and defensible decisions related to the preservation and rehabilitation of a pavement network. It helps the decision makers select the right treatment on the right road at the right time. The project-level PMS supports decisions about the best treatment to apply to a selected section of pavement based on a detailed Pavement Evaluation.

### Inventory and Condition Assessment

The first and foremost component before any analysis can be performed is asset inventory and condition assessment, in which a wide range of relevant data on the infrastructure network are collected, such as size, type, material, age, design standard, descriptive information, etc. The asset inventory data and inspection records will need to be reviewed, merged and digitized into a database. In addition, GIS formatted data and visualizations(e.g., graphics, tables) may be integrated to support search, display, and statistical analysis in a consistent digital format.

In addition to the characteristics and performance information, asset management requires the following types of data for every type of asset. This list is defined in the 2013 Transportation Asset Management - A Focus on Implementation (AASHTO, 2013) from a perspective of transportation infrastructure. Similar categories of data can be applied to other types of infrastructure.

- Geographic location, including route/milepost, a linear referencing system if separate from route/milepost, latitude/longitude, and corridor definitions.
- Jurisdiction data, such as district and administrative subdivisions of the department, county, municipality, political districts, ownership, and maintenance responsibility.
- Functional and utilization data such as functional class, number of lanes, speed, and tolling; presence of curbs, sidewalks, and other user features; special-purpose networks such as the National Highway System, the Strategic Highway Network, and freight networks; presence of school bus and transit routes; and presence of utility lines.
- Performance characteristics such as access restrictions, roadway geometry, obstructions, medians, and safety features.
- Construction history and historical significance.
- An archive of valuable documents, often a multi-media file repository.

## Performance Measure and Targets

The “performance target” analysis is usually conducted to define 1) performance measures, 2) performance targets, and 3) performance gaps. According to NCHRP 08-36, condition-based performance measures are commonly used for effective decision-making about preservation, needs assessment, target setting, risk analysis, and communication of results. Condition measures can include directly collected data, such as the IRI and bridge condition ratings, or derived measures such as remaining service life or customer satisfaction surveys. Below is a summary of common bridge performance measures (Figure 5).

| Measure | Description | Notes |
|---|---|---|
| Good/Poor Condition | Calculated based on minimum value of NBI deck, superstructure, substructure and culvert ratings | Required for NHS bridges |
| Structurally Deficient (SD) | Calculated based on minimum value of NBI deck, superstructure, substructure and culvert ratings | Equivalent to Poor condition |
| Sufficiency Rating (SR) | 0-100 measure indicating a bridge’s overall sufficiency to remain in service 0 indicates an entirely insufficient bridge; 100 indicates one that is entirely sufficient | Includes structural and functional considerations; formerly used to establish eligibility for Federal funding |
| Health Index | 0-100 measure indicating overall bridge condition based on element-level data; 0 indicates all elements are in CS4, 100 indicates all are in CS1. | Summarizes element level conditions, does not include consideration of functional or geometrical issues |

| | | |
|---|---|---|
| Posted Bridges | Count of bridges posted with load limits; specified through NBI Item 41 | A number of States track posted bridges; posting practices vary |
| Remaining Service Life | A bridge's estimated remaining economic life | Calculation complicated by number of bridge components and feasible treatments |
| Functionality Obsolete (FO) Status | Identifies bridges with functional or geometrical issues; calculated based on a variety of NBI items | Previously used with SD and SR used by FHWA to establish funding eligibility |
| High Risk Bridges | Count or % of bridges considered high risk due to likelihood of service disruption and impact of service disruption | Examples include scour critical bridges, fracture critical bridges, bridges with clearance restrictions and seismic vulnerability |

**Figure 5**: Common bridge performance measures (FHWA, 2017)

Examples of performance measures are pavement condition index for roads or bridge condition index for bridges, as shown in Figure 6 and Figure 7, respectively.

| | Good | Fair | Poor |
|---|---|---|---|
| IRI (inches/mile) | <95 | 95-170 | >170 |
| Rutting (inches) | <0.20 | 0.20-0.40 | >0.40 |
| Faulting (inches) | <0.10 | 0.10-0.15 | >0.15 |
| Cracking (%) | <5 | 5-20 (asphalt) 5-15 (JCP) 5-10 (CRCP) | >20 (asphalt) >15 (JCP) >10 (CRCP) |
| PSR | PSR ≥ 4.0 | 2.0 ≤ PSR ≤ 4.0 | PSR ≤ 2.0 |

| | Pavement Type | | |
|---|---|---|---|
| | Asphalt and Jointed Concrete | Continuous Concrete | |
| Overall Section Condition Rating | 3 metric ratings (IRI, cracking and rutting/faulting) | 2 metric ratings (IRI and cracking) | Measures |
| Good | All three metrics rated "Good" | Both metrics rated "Good" | → percentage of lane-miles in "Good" condition |
| Poor | ≥ 2 metrics rated "Poor" | Both metrics rated "Poor" | → percentage of lane-miles in "Poor" condition |
| Fair | All other combinations | All other combinations | |

**Figure 6**: Pavement performance measure calculation (23 CFR § 490.313)

| | NBI Rating Scale (from 0 – 9) | 9 8 7 Good | 6 5 Fair | 4 3 2 1 0 Poor |
|---|---|---|---|---|
| Bridge | Deck (Item 58) | ≥7 | 5 or 6 | ≤4 |
| Bridge | Superstructure (Item 59) | ≥ 7 | 5 or 6 | ≤ 4 |
| Bridge | Substructure (Item 60) | ≥ 7 | 5 or 6 | ≤ 4 |
| | Culvert (Item 62) | ≥ 7 | 5 or 6 | ≤ 4 |

**Figure 7**: Bridge condition rating thresholds for classification (FHWA, 2017)

Performance target and gap analyses are conducted to define quantifiable levels of performance to be achieved within a certain time period, and to identify deficiencies hindering progress to achieving a state of good repair and system performance effectiveness. Analyses of historical and current data are needed to determine performance trends and gaps, including both immediate gaps that need closing in the near term and long-term gaps that need closing in stages. It also involves analysis of alternative funding levels and allocation strategies to compare differences in long-term outcomes.

### Deterioration or Performance Modeling

Deterioration or performance modeling, as one of the most important analytical components of infrastructure asset management, models deterioration process due to various stressors such as aging, traffic, or climate and other environmental factors, and predicts the future conditions of infrastructure assets. Depending on data availability and type of assets, deterioration or performance models are developed in either deterministic or probabilistic form by mechanistic, empirical, or statistical, or machine learning approaches.

The pavement performance models adjust the estimated condition of each pavement section based on the analysis year (age). Pavement Performance Models can be developed by subdividing the pavement network data into those sections that have received no treatments (new pavements) and those that have received specific treatments and analyzing the change in condition over time for these pavement sections. Before any data is collected for the agency's road network, pavement management system (PMS) software usually uses a default pavement performance or deterioration model to age the pavement sections that will not be treated between analyses to perform the economic analyses. After a specific time period (e.g., 5 years or more of pavement condition data collection) the weighted-average condition index for a given age can be used to refine the performance model(s). The more sophisticated PMS software programs can use separate performance models for new roads, pavement preservation treatments, and pavement rehabilitation treatments. In addition, different pavement condition resets can be applied after the treatment is applied in the analysis. Not all treatments reset the condition of the pavement to a PCI of 100 after a treatment is applied. Some PMS software programs allows input of a performance model equation to define the pavement deterioration, user can adjust the equation based on truck traffic levels and average truck weights. These can be further adjusted in the future based on real pavement condition data.

Existing bridge deterioration models mechanistic models that aim to simulate deterioration processes and statistical/empirical (probabilistic) models that are based on historical condition data and/or expert elicitation. These models incorporate different forms, levels of sophistication, assumptions, and data format. For example, probabilistic deterioration models can be developed based on National Bridge Inventory (NBI) data at the component level, or the more granular National Bridge Element (NBE) data at the element level. Depending on the needs and data availability, the probabilistic deterioration models can be deterministic (e.g., regression models), stochastic (e.g., Markov, hazard-based duration models), and data driven (machine-learning models). Regardless of the granularity in which deterioration is modeled, input variables are needed to predict the rate of deterioration. Input variables may include the environmental exposure and location of a bridge, loading and traffic conditions, materials, and construction methods, among others. Deterioration models that are used in practice are usually simplified.

### Life-Cycle Cost Analysis (LCCA) and Life-Cycle Planning (LCP)

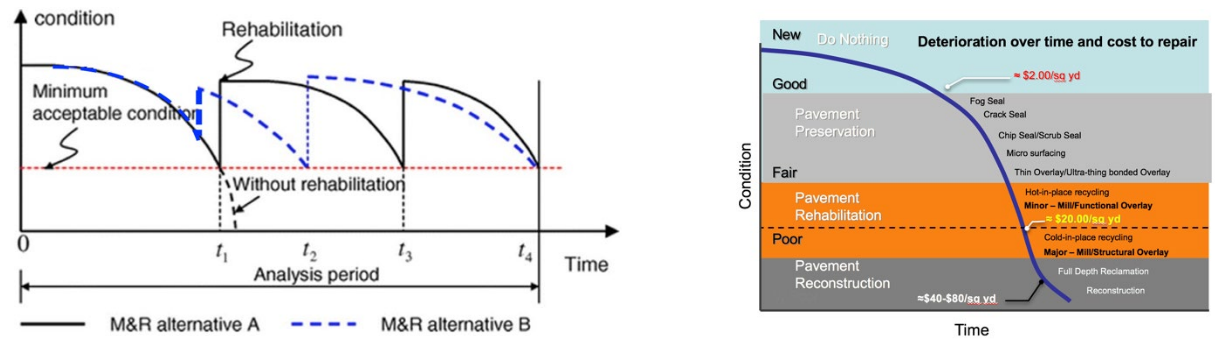
Life-Cycle Cost Analysis (LCCA), as an essential component in TAM, is an effective analytical approach for evaluating the total economic worth of project alternatives considering all types of cost (upfront and in future). In infrastructure asset management framework, life cycle cost analysis (LCCA) and life cycle planning (LCP) identify whole life management strategies for assets to minimize life cycle cost, maximize performance or other objectives. These strategies are the best sequence, frequency and combination of maintenance, preservation, repair, rehabilitation, and replacement (reconstruction) treatments for bridges over their lifecycle.

LCCA is performed at project-level that compares different design or treatment alternatives/strategies for a single project or asset, while Life Cycle Planning determines a strategy for managing an asset over its life to achieve target level performance while minimizing life cycle costs. According to FHWA 23 CFR 516 and 667 (FHWA, 2016), LCP planning is performed at the network level considering the needs of all or a subset of assets in a system over an analysis period sufficiently long to include at least one lifecycle for the asset class under consideration. Both LCCA and LCP use inventory and condition data, performance objectives, deterioration models, financial information, and treatment rules to determine the most cost-effective strategies for preserving or improving asset performance over the long term.

Federal requirements for the TAMP state that LCP include the following:

- Identification of deterioration models
- Potential work types, including treatment options and unit costs
- A strategy for minimizing life cycle costs and achieving performance targets
- Asset performance targets

Figure 8 shows two examples of LCCA and management decision-making in bridge and pavement problems.




(a) (b)

**Figure 8**: (a) Example of life cycle condition and cost comparison of different maintenance scenarios in bridge management. (b) Example of condition-based maintenance decision-making in pavement management

### Financial Planning

The LCCA and LCP analyses set the foundation for high-level capital planning and optimization. The financial plan can establish how the agency will address the resources needed to achieve and sustain the long-term asset management objectives.

Financial and budget planning analyses can use LCCA-based modeling (e.g., optimization or simulation) to evaluate, compare and determine the optimal funding and allocation scenarios in both short term and long term. It also prioritizes capital projects and optimizes investment decision strategies. In essence, such models are able to simultaneously address multifold cost trade-offs (e.g., preventive versus corrective actions, direct cost versus logistical/management cost, present and future expenses, etc.) to determine the optimal capital plan at a strategic level, in order to achieve various performance objectives (e.g., maximum benefit for budget spent).

## 2.5 Risk and Resilience Analysis

When faced with unforeseen circumstances, such as heavy weather patterns and natural hazards due to climate change, transportation agencies take a multi-faceted approach to identify, quantify, and mitigate the threats to transportation infrastructure assets; all of which are encompassed in risk management—an important aspect of infrastructure asset management. Federal legislation requires state transportation departments to develop a risk-based asset management plan for pavement and bridges on the National Highway system (NHS). Risk and resilience analysis helps infrastructure owners in maximizing the duration and service performance of capital-intensive infrastructure and optimally allocating their limited financial resources, anticipating various natural and human-caused hazards.

Agencies are, more than ever, in need of clear, concise methodology to guide them as they prioritize assets and decide which assets are most in need of repairs and updates. We will review two prevalent methodologies (1) USDOT VAST Based Approach, and (2) ASME's Risk Analysis and Management for Critical Asset Protection (RAMCAP) Plus Approach and adapt them for transportation infrastructure risk and resilience analysis.

This review will summarize and compare these two approaches, which will later be utilized in 3.4 in a case study on how these methodologies can be applied to calculate the risk of roadway segments in St. Thomas, a U.S. Virgin Islands.

### FHWA's Vulnerability Assessment and Adaptation Framework

First published in 2012 and most recently updated in 2018, the Federal Highway Administration's *Vulnerability Assessment and Adaptation Framework* (VA Framework) provides a methodology for assessing the vulnerability of a transportation asset to weather and climate events. This framework defines a seven-step process for transportation agencies to follow to complete their vulnerability assessment. These seven steps are listed below.

**Step 1: Articulate Objectives and Define Study Scope**
The transportation agency defines the purpose and goals of the study and selects relevant assets and weather events to consider.

**Step 2: Obtain Asset Data**
The agency collects data concerning the assets' condition, location, travel volume, and any other aspect relevant to the assets' functionality.

**Step 3: Obtain Climate Data**
The agency obtains climate data by either collecting existing data or making their own projections. One useful tool for collecting this data is the USDOT's Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool.

**Step 4: Assess Vulnerability**
The agency determines the vulnerability of each facility and system to climate change. The Framework defines vulnerability as a function of exposure (whether the asset or system is in a location at risk for climate effects), sensitivity (how the asset or system's functionality would be affected by the event), and adaptive capacity (the asset or system's ability to cope with the impacts). The agency can determine vulnerability by interviewing, surveying or holding workshops with stakeholders and regional experts, by analyzing indicators, or by making an informed engineering assessment.

**Step 5: Identify, Analyze, and Prioritize Adaptation Options**
The agency can then identify possible adaptation options for those assets or systems determined to be the most vulnerable to the weather or climate scenarios. They then weigh the costs of different adaptation options against their effectiveness to determine which are optimal.

**Step 6: Incorporate Assessment Results in Decision Making**
The optimal adaptation options are considered to determine what strategies to implement.

**Step 7: Monitor and Revisit**

The agency establishes a monitoring and evaluation plan for their assets and continually keeps track of relevant data ("Vulnerability Assessment and Adaptation", 2017).

## USDOT's VAST Risk Assessment Tool

The U.S. Department of Transportation derived the Vulnerability Assessment Scoring Tool (VAST) from the FHWA's VA Framework to select appropriate indicators and collect data based on how they are characterized. Developed by USDOT in 2015, the VAST is an Excel spreadsheet tool that is used to collect information about indicators of each component of vulnerability and operationalizing information into relative vulnerability scores. As a result, agencies can calculate vulnerability scores using the following steps.

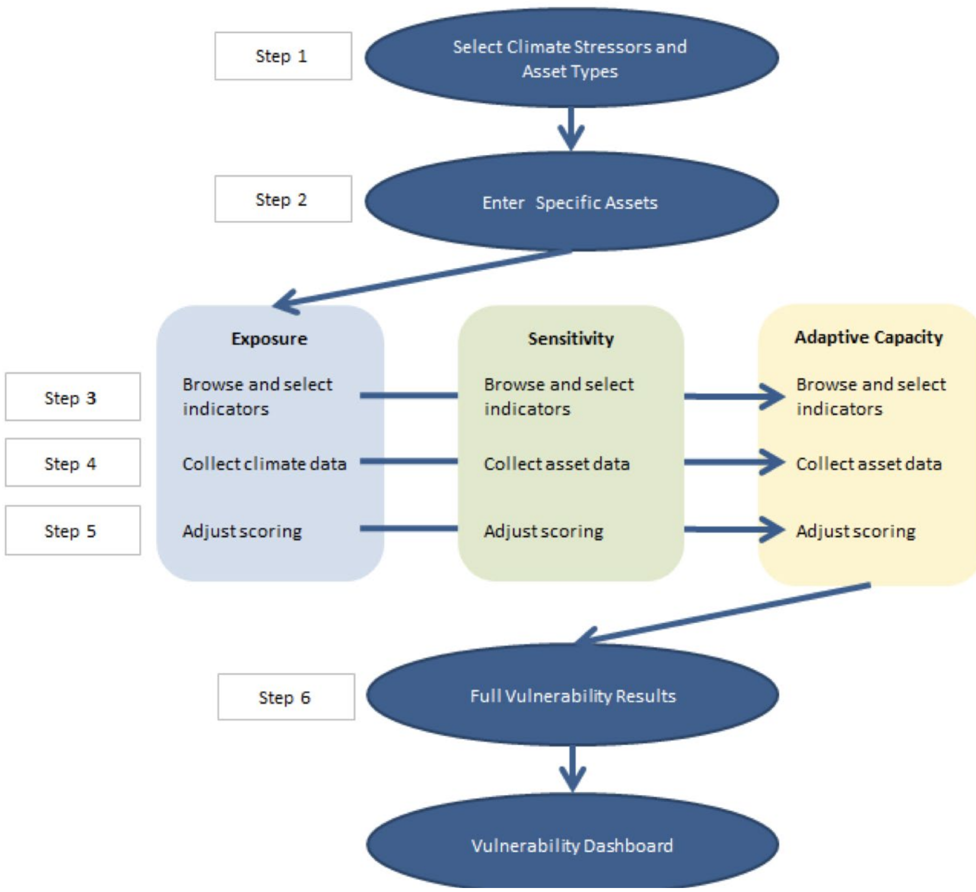



**Figure 9**: VAST approach flowchart

### Step 1: Climate Stressor

Each asset is distinguished from one another based on its relevant climate stressors, such as (1) increased temperature and heat, (2) precipitation-driven inland flooding, (3) sea-level rise/extreme high tides, (4) storm surge, (5) wind, (6) drought, (7) dust storms, (8) wildfires, (9) winter storms, (10) changes in freeze/thaw, and (11) permafrost thaw, are used to track continuities in hazard patterns in certain regions.

**Step 2: Asset Type**
Another way assets are characterized from each other are by their own modes or types. Asset types covered in this tool are (1) rail, (2) ports and waterways, (3) airports and heliports, (4) oil and gas pipelines, (5) bridges, and (6) roads and highways. When paired with climate stressors, agencies may draw connections between the climate and asset type to predict which types of assets are prone to a specific weathering hazard.

**Step 3: Exposure Analysis**
Identifications of both climate stressors and asset types provide agencies with a framework for collecting their data using exposure indicators, such as proximities to specific locations and its presence in a specific zone, represented by a score and percent resilience in a 100-year period.

**Step 4: Sensitivity**
The Sensitivity Indicator Library provides ideas for sensitivity indicators which are specific to asset-stressor combinations. The indicators are weighted in arriving at an overall sensitivity score.

**Step 5: Adaptive Capability Analysis**
Understanding the resilience of transportation infrastructure requires agencies to identify the hazards, then research repairs and updates necessary to salvage these assets. Adaptive Capacity Indicators may include but are not limited to replacement cost ($), detour length (mi/km), disruption duration (days), and location criticality score.

**Step 6: Vulnerability Scoring**
A vulnerability score is then calculated after analyzing an asset's exposure indicators, sensitivity indicators, and adaptive capacity indicators.

### ASME's RAMCAP Plus Approach
The ASME's Risk Analysis and Management for Critical Asset Protection (RAMCAP) Plus approach was developed as a result of the consequences of the attacks on September 11th, 2001. It provides a guide for adapting and maintaining an agency's most critical assets that emphasizes the threat of terrorist attacks, producing measurements of monetized annual risk and resilience (cost per year). Similar to the USDOT approach, the RAMCAP approach selects relevant assets and weather events to consider before obtaining and analyzing climate and asset data, but it places more emphasis on a user's relationship with an asset (for instance, the vehicle operating costs or total user consequence).

**Step 1: Asset Characterization**
To begin this approach, the agency would need to identify the assets based on their criticality and asset type. In doing so, the RAMCAP sector-specific guides contain a "Top Screen" process to help them determine the asset's criticality based on their type. Those with the greatest negative effect on the system's ability to operate are considered as the high priority assets.

**Step 2: Threat Characterization**
The agency identifies threats relevant to each critical asset, ranging from probable threats that have consistently occurred over the past and the worst possible consequences that could occur. The consideration of the worst hazard for an asset allows an agency to mitigate the probability of it occurring.

**Step 3: Consequence Analysis**
An analysis of the worst hazard requires an agency to consider the repercussions that come with this scenario. Examples of consequences include fatalities, serious injuries, and economic impacts, such as financial losses to the agency the asset is owned by and economic losses to the community the asset serves.

**Step 4: Vulnerability Analysis**
The agency predicts the probability an event will occur given the worst possible circumstances. Such analysis is conducted through consultation with experts, usage of Vulnerability Logic Diagrams (VLD), usage of Event Trees, or some combination of methods.

**Step 5: Threat Assessment**
The likelihood of each event occurring on each asset is estimated with the data from the aforementioned steps. This probability is represented as a metric with a positive value between 0 and 1.

**Step 6: Risk and Resilience Assessment**
While risk is calculated to holistically represent all users, resilience is calculated using separate equations for the owner of the asset and the community:

$$\text{Risk} = \text{Consequences} \times \text{Vulnerability} \times \text{Threat Likelihood}$$
$$\text{Resilience}_{\text{Owner}} = \text{Lost Revenue} \times \text{Vulnerability} \times \text{Threat}$$
$$\text{Resilience}_{\text{Community}} = \text{Lost Economic Activity in the Community} \times \text{Vulnerability} \times \text{Threat}$$
$$\text{Lost Revenue} = \text{Duration of Service Denial} \times \text{Severity of Denial} \times \text{Price per Unit}$$

**Equations 1**: RAMCAP Plus risk and resilience cost calculations

Lost Economic Activity in the Community is the amount in losses of economic output to direct customers and indirect losses throughout the community.

### Comparing the VA Framework/VAST and RAMCAP Approach
The FHWA's VA Framework and the ASME's RAMCAP Approach differ in the type of threat the methods aim to protect assets against. The VA Framework is focused on climate and weather-related events (temperature, precipitation, floods, etc.), while the RAMCAP Approach focuses more on terrorist attacks. The VA Framework emphasizes the acquisition of climate data and lists specific guidelines for every kind of climate event. The RAMCAP Approach, on the other hand, was developed in the wake of the attacks on September 11th, 2001, and, while it is purported to be an "all-hazards" approach, it is clearly geared towards human-caused disasters and terrorist attacks. This is evidenced by the fact that RAMCAP guidelines incorporate into their vulnerability

assessment the categories of vehicles which could be used to attack an asset and by the fact that RAMCAP contains specific guidelines for the "weaponization" of an asset.

The other main difference between the VA Framework and the RAMCAP Approach is that the RAMCAP Approach is more quantitative in nature. The RAMCAP Approach gives explicit equations for calculating risk and resilience, while the VA Framework gives only loose criteria to be considered in an assessment of vulnerability. Because of this, the RAMCAP Approach is more clearly defined and easier to replicate, but the VA Framework is adaptable and leaves more room for stakeholder engagement.

Finally, the VA Framework heavily emphasizes collection of data, while the RAMCAP Approach emphasizes using internal knowledge and logic. The VA Framework lists many climate research centers from which an agency could acquire data. Meanwhile, the RAMCAP Approach emphasizes thought experiments like Event Trees, where a group determines every path an attacker could take and how they could succeed or fail at each step. Additionally, the VA Framework encourages cross-coordination with other groups and agencies and stakeholder engagement while the RAMCAP Approach seems more geared towards a single agency working in relative solitude.

**Table 3**: Comparison of USDOT VAST and ASME RAMCAP Analyses

| **Level of Analysis** | **Macro-Level, Semi-Quantitative Analysis** | **Detailed Quantitative Analysis** |
|---|---|---|
| **Method** | USDOT VAST Approach | ASME RAMCAP-based Approach |
| **Output** | Vulnerability Scores | Risk and Resilience Measures ($/year) |
| **Component & Procedure** | 1. Climate Stressor<br>2. Asset Type<br>3. Exposure Analysis<br>4. Sensitivity Analysis<br>5. Adaptive Capability Analysis<br>6. Vulnerability Scoring<br><br>The composite vulnerability scores for each asset are calculated using a weighted average of the exposure, sensitivity, and adaptive capacity scores. | 1. Asset Characterization<br>2. Threat Characterization<br>3. Consequence Analysis<br>4. Vulnerability Analysis<br>5. Threat Assessment<br>6. Risk and Resilience Assessment<br>7. Risk and Resilience Management<br><br>**Risk** = Consequences * Vulnerability * Threat Likelihood<br><br>**Resilience** $_{\text{Owner}}$ = Lost Revenue * Vulnerability * Threat<br><br>**Resilience** $_{\text{Community}}$ = Lost Economic Activity in the Community * Vulnerability * Threat |

## The CDOT Method

Another relevant assessment tool for risk analysis is the Colorado Department of Transportation (CDOT) Method—a risk analysis approach itself derived from the RAMCAP Approach for specifically highway infrastructure. These methods follow a seven-step process to execute risk analysis. While the RAMCAP Plus Approach interprets risk as the expected value of consequences from specific terrorist attacks and natural disasters, the CDOT method is tailored specifically to addressing potential vulnerabilities in transportation assets, specifically for inland flash flooding, rock fall, and fire debris hazards to roadways, bridges, and culverts.

As a result, a series of recommendations can be made based on the results of risk analysis by comparing costs and benefits of different risk mitigation scenarios. In each scenario, we can establish a defined priority of highway assets and predict the financial impacts for highway asset owners (transportation agencies) and users to incur in protecting themselves from various physical threats. Figure 10 below shows the risk assessment procedure that we derived from the three existing frameworks, primarily the CDOT method.

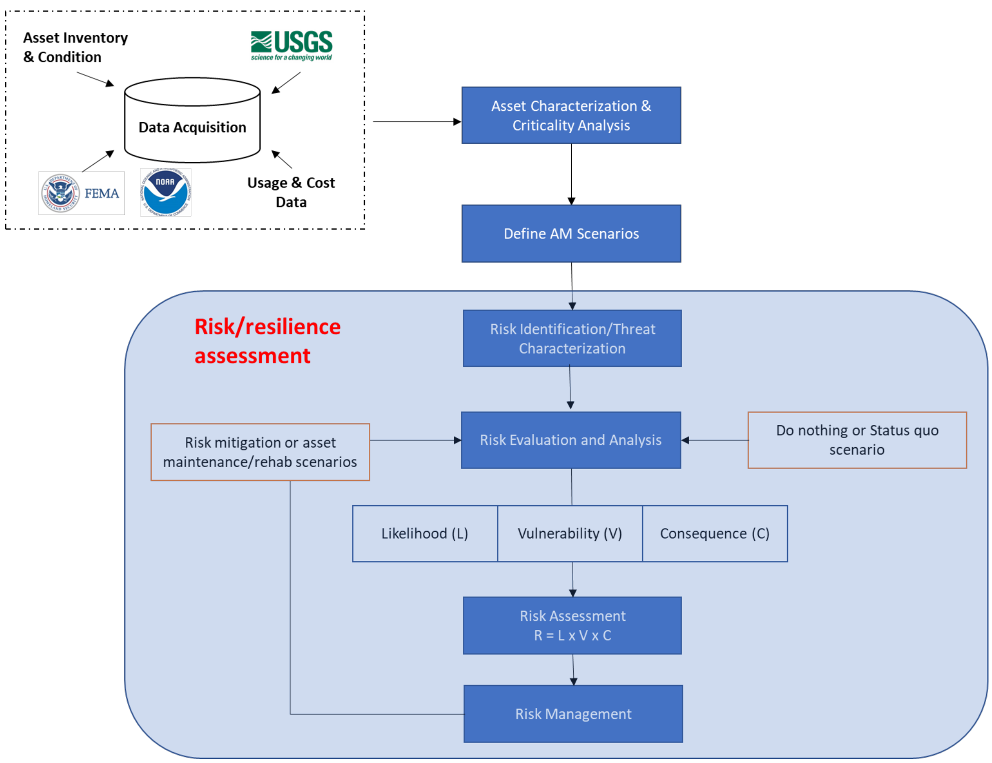



**Figure 10**: Our risk assessment procedure as part of the overall AM framework

The first step is asset characterization. To characterize specific assets, it is imperative to understand the types of assets within the provided data to know which ones are critical and which should be considered. Throughout this project, the CDOT method was applied to collected data for floodplains, from Federal Emergency Management Agency (FEMA) flood maps; soil types, from U.S. Department of Agriculture (USDA) soil surveys; elevations or slopes, from the United States Geological Survey (USGS); and existing pavement conditions, maintenance costs, and traffic, all from the local DOT or transportation agency. Spatial data sets can be accumulated by aggregating areas of land with their individual attributes.

## 2.6 Economic Impact Analysis

Transportation infrastructure plays an important role in supporting the productive activities of an economy. Besides the direct costs to infrastructure owner and users, the total economic impact of infrastructure damage and failure in natural hazardous events could be much broader, which is not typically measured or understood until after their failure or absence causes impactful disruptions in an otherwise well-functioning economy. The broader economic and community impact is an important aspect in quantifying the resilience of transportation infrastructure.

Before further analysis to support risk management decision making, it is necessary to understand the full benefits and costs of each of the intervention/investment scenarios for the public, government, and the overall macroeconomic economy, relative to a baseline scenario, such as a "do nothing" status quo scenario. We identify the following economic impacts of transportation infrastructure failure. (Note that some of the cost items are direct user and agency costs and are usually included in risk assessment and asset management life cycle cost estimation.)

1. **User costs associated with poor transportation infrastructure**

Poor conditioned or damaged infrastructure results in increased delays and detours from slowing traffic, potholes, and temporary closures. Based on data on the average traffic and additional time due to detours, the following measures will be estimated:

a. **Wear and tear on vehicles:** Previous literature finds that any road segment with a pavement condition PSI rating of less than 3.5 will result in additional per-mile maintenance costs in terms of increased maintenance, repairs, tires, and depreciation costs. These costs will be estimated based on road usage and infrastructure condition rating for both personal vehicles and trucks.
b. **Lost time/productivity due to traffic and detours**: Because peak hour traffic usually occurs during commute times, the productivity loss estimates will be based on the morning commute delays of workers using the roadways. In addition to lost time for the individual delayed due to roadwork or poor infrastructure, when someone is late, others who are dependent on them are idle as well (even if they are not stuck in traffic). This loss would be greater with the variance (unpredictability) of the delay. These losses may be estimated based on avoidable annual time delays and the median average wage of the Territory.
c. **Gas and pollution costs**: Extra time in traffic increases the time commuters are idling in their vehicles. This idling time increases gas costs and pollution. Our estimates will use data from INRIX and the Environmental Protection Agency to estimate the amount the gas and $CO_2$ emissions expended by this traffic.

d. **Safety implications:** Poorly maintained roads, as well as added congestion due to insufficient roadways or detours, increase frequency and severity of accidents. Based on correlation analysis of accident severity and frequency will road conditions by Zaoloshnja and Miller, our analysis will calculate the added costs of accidents due to subpar roadway conditions.

2. **Costs associated with reactive government road maintenance**

Currently, much infrastructure maintenance is performed on an as-needed, reactionary basis. Because of these practices, maintenance typically employs basic technology which results in higher per-mile maintenance costs compared to systematic maintenance, e.g., an LCCA-based asset management approach. Infrastructure budget and purchase order information can be used to understand the average unit costs of maintenance based on the type of intervention. These unit costs will be used to calculate the total budget necessary to elevate the PSI of each road to a higher level.

3. **Macroeconomic constraints for poor infrastructure**

The gains associated with improved maintenance directly affect citizens but also have real economic implications. A common macroeconomic indicator of economic growth is real GDP per capita, sometimes referred to as standard of living. There are several determinants of economic growth that can lead to a healthier economy, higher productivity, and an increased growth in real GDP per capita.
Investment in infrastructure is a form of growth of an economy's *public* capital stock and can directly lead to an increase in labor productivity in the private sector, leading to an overall increase in real GDP growth. Conversely, when an economy's public capital stock is allowed to decline, the results can lead to slower private sector productivity growth.

Recent literature has found strong linkages between public sector capital stock investment and private sector productivity. A review of several papers found that a 10 percent increase in an economy's public capital stock would lead to private sector output/GDP of 1.5 to 2 percent (Bom & Ligthart, 2009; Rioja, 2013). The total rate of return of public infrastructure investment, based on several studies, has been found to be somewhere between 30 and 40 percent.

Additionally, the investment in public infrastructure creates not only private sector productivity growth in the long run, but also adds short term impacts from an injection of local spending. Recent studies estimate that for every $1 of public investment in infrastructure, the local economy realizes a total impact of $1.57 (Zandi, 2010). Similar studies estimate the impacts to be between a multiplier of between 1.5 and 1.9. To put this in perspective, the estimated multiplier resulting from increased spending in infrastructure is up to six times higher than other expansionary fiscal policies such as temporary (0.24 to 1.24) and permanent (0.32 to 0.50) tax cuts. Infrastructure spending has a similar impact to other increased government spending such as expanded unemployment benefits (1.60), temporary federal financing of work-share programs (1.69), and increased aid to state governments (1.41).

In order to understand how the improved infrastructure will impact the overall economy, two models may be utilized:

- **Total Economic Impact of Subpar Roadways:** The first estimates the direct, indirect, and induced costs associated with subpar roadways to generate the total economic loss within the Territory. The estimates from Part A (productivity loss and safety implication costs) will be modeled using input-output modeling to project the annual macroeconomic costs associated with subpar infrastructure.
- **Productivity Constraints of Subpar Public Capital Stock**: As revealed from recent literature, lack of public capital stock can result in constrained private sector growth. Based on the findings from Part B (total needed investment to get roadways to a desired level of service), this model estimates the effect of increased efficiency and improved roadway infrastructure on the regional or local GDP.

These two models combined demonstrate the current impacts of improved infrastructure maintenance investment. The total direct citizens costs and macroeconomic costs can be compiled into the total costs associated with the improved infrastructure maintenance in the study region.

## 2.7 Decision Analysis and Recommendations

The quantitative results of the above steps were used for supporting investment and management decisions through standard benefit cost analysis (BCA), prioritization analysis, optimization modeling, etc. We present an example case study in the next section to illustrate the application of benefit cost analysis to determine the best investment strategy the quantitative risk assessment and asset management analysis.

In addition, risk assessment and asset management can be integrated to enable well-informed decision making. Risk and resilience factors could be included in the essential components/analysis of asset management, such as deterioration modeling, life cycle cost analysis, and capital planning.

The deterioration process of the infrastructure assets should be modeled under both normal and hazardous conditions. Incorporating risk and resilience analysis into deterioration modeling helps to understand the impacts of hazards and maintenance, repair, and rehabilitation (MR&R) levels on asset deterioration and condition in both the short and long term. The framework will identify various MR&R scenarios and/or alternative strategies to evaluate their impact on the future condition of infrastructure assets.

The purpose of risk- and resilience-based LCCA and capital planning is to understand the various benefits and costs of different MR&R strategies and find the optimal level of investment to maximize system performance (e.g., reliability, level of service, resilience) while also minimizing the life cycle cost and risks. It involves identifying the cost associated with each of the MR&R scenarios and risk and resilience metrics to perform life cycle cost analysis for the infrastructure asset system. Risks and resilience metrics will also be incorporated into decision-making models for capital planning (e.g., decision tree-based simulation, optimization) to determine:

- The minimum budget needed to sustain state of good repair or achieve performance goals of the infrastructure system;
- the best, average, and worst performance level that can be achieved at a given budget, and;
- which assets should be maintained first prior to others to produce the lowest system life cycle cost and risk.

# 3 USVI Analysis and Case Study

In this section, we apply the analytical framework to USVI to develop a series of risk-based asset management analysis step by step. By either quantitative or qualitative analysis on illustrative examples, we demonstrate how to pull and utilize data from various sources to assess life cycle cost and economic impact of maintenance scenarios on infrastructure and risk resilience analysis under the extreme natural condition and economic impact.

## 3.1 Asset Characterization and Criticality Analysis

The scope of this case study is limited to transportation infrastructure for the three main islands of the USVI territory, St. Croix, St. Thomas and St. John. Given the scope of this study and the availability of data, we focus on roadway pavements and bridges, which are among the most critical types of highway transportation infrastructure. The natural hazard we are focusing on is flooding, both coastal and riverine, as it is one of the most predominant natural threats in the coastal environment of USVI.

### Data Sources

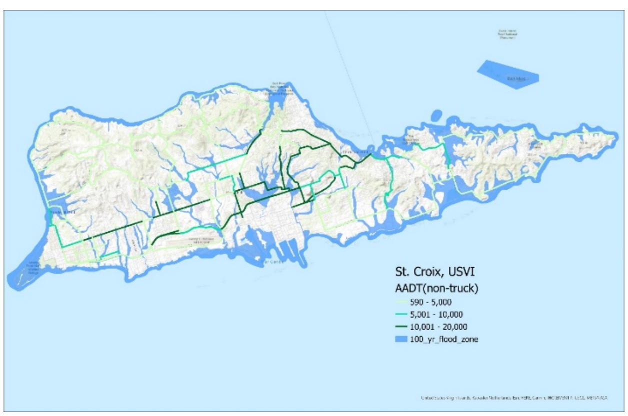
Our partners from the University of Virgin Islands (UVI) and USVI Department of Public Works (DPW) provided most of the infrastructure data. We collected natural hazard data from public sources. Most of the economic parameter values are assumed based on literature and expert elicitation. Below is a list of key datasets and sources.

1. Roadway Infrastructure
    1. USVI major and minor roadway network
    2. Pavement rating record (2017)
    3. Traffic data (2009) from USVI DPW

    4. Roadway damage report (2018)
    5. Pavement maintenance cost from USVI DPW
2. Bridge Infrastructure
    1. Bridge Inspection Reports (2013)
    2. Bridge NBI rating (2019 and 2020) from FHWA InfoBridge™ database
3. Safety Data from the Virgin Islands Offices of Highway Safety 2019 Annual Report
4. Flood Risk
    1. 100-year flood plain map layer from FEMA National Flood Hazard Layer (NFHL)
    2. Sea level rise scenario layers from NOAA Sea Level Rise Viewer

### 3.1.2 Criticality Analysis

We applied the criticality analysis criteria (Table 1) developed in section 2.2 to determine the criticality levels of transportation infrastructure. These criteria were developed based on information in literature and discussions with subject matter experts in the team. The AADT and AADTT data were obtained and processed from the 2010 USVI DPW Traffic Collection Report. Below shows the map views of the criticality levels in terms of three of the four criteria- AADT, AADTT, and network redundancy- for all three islands.

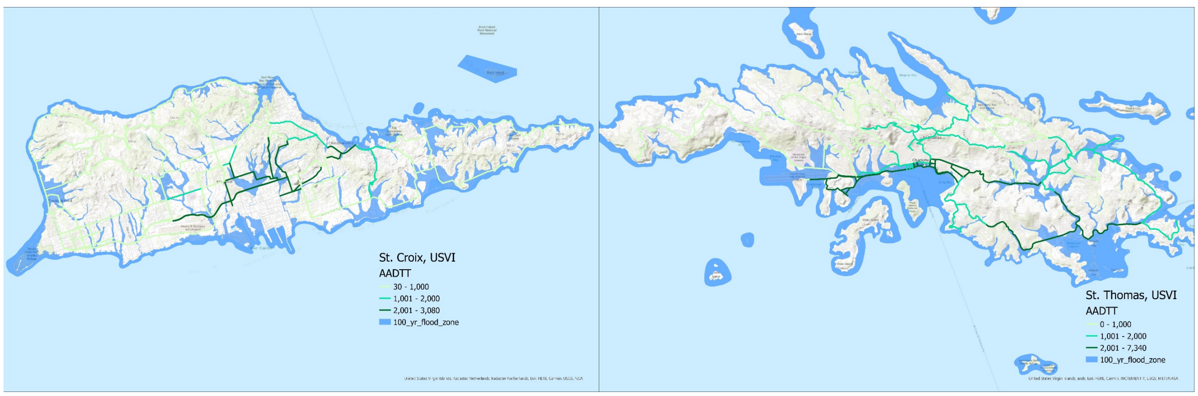



(a)


(b)


(c)

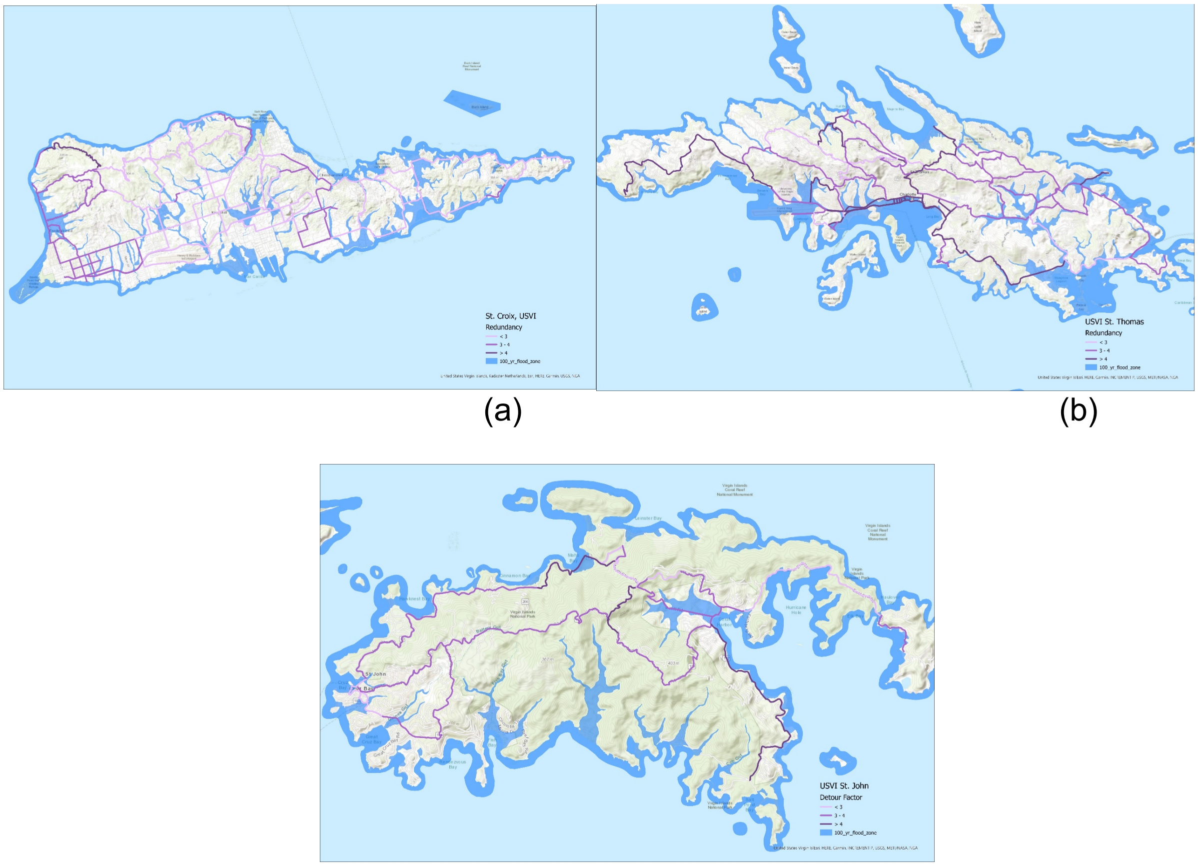
**Figure 11**: Criticality levels of USVI roadway network based on AADT for (a) St. Croix, (b) St. Thomas, and (c) St. John




(a) (b)


(c)

**Figure 12**: Criticality levels of USVI roadway network based on AADTT for (a) St. Croix, (b) St. Thomas, and (c) St. John




(a) (b)

(c)

**Figure 13**: Criticality levels of USVI roadway network based on redundancy for (a) St. Croix, (b) St. Thomas, and (c) St. John

***Location***

To categorize the location criticality of transportation infrastructure assets, we identified a set of key facilities of the territory in four categories, i.e., freight port, transit terminals, top tourism sites, and lifeline/emergency facilities.

**Table 4**: Selected USVI key facilities

| | Freight port | Transit Terminal | Top Tourism Site | Lifeline/Emergency Facility |
|---|---|---|---|---|
| **St. Croix** | • Ann E. Abramson Marine Facility,<br>• Gallows Bay Dock<br>• Wilfred "Bomba" Allick Port<br>• Gordon A. Finch Molasses Pier | • Ann E. Abramson Marine Facility<br>• Svend Aage Ovesen Jr. Seaplane Terminal<br>• Henry Rohlsen International Airport | • St George Village Botanical Gardens<br>• Sandy Point National Wildlife Refuge | • Juan F. Luis Medical Center<br>• Richmond Power Plant/Substation |

| | | | | |
|---|---|---|---|---|
| **St. John** | • Theodore Eric Moorehead Marine Facility (Enighed Pond) | • Loredon L. Boynes Sr. Dock<br>• Victor William Sewer Marine Facility (the “creek”)<br>• Cruz Bay Ferry Terminal | • Cruz Bay Town (visitor center)<br>• Trunk Bay Beach<br>• Cinnamon Bay Beach<br>• Maho Bay Beach<br>• Honeymoon Beach | • Myrah Keating Smith Health Center |
| **St. Thomas** | • Austin "Babe" Monsanto Marine Facility<br>• Crown Bay Cargo Port<br>• Urman Victor Fredericks Marine Terminal (Red Hook) | • Crown Bay Marina<br>• Edward Wilmoth Blyden IV Marine Terminal<br>• Charles F. Blair, Jr. Seaplane Terminal<br>• The Waterfront<br>• West Indian Company Ltd. Dock<br>• Cyril E. King Airport | • Charlotte Amalie Downtown<br>• Crown Bay Center<br>• Havensight Mall<br>• Magen’s Bay Beach<br>• Lockhart Garden Shopping Center | • Roy Lester Schneider Hospital<br>• Harley Power Plant/Sub |

We measure the distance from each roadway/bridge asset to these key facilities to quantify the location criticality of transportation infrastructure assets. Below are maps showing the color-coded three criticality levels by key facility location.


**Figure 14**: Criticality levels of USVI roadway network based on location for St. Thomas

**Figure 15**: Criticality levels of USVI roadway network based on location for St. John

## 3.2 Intervention Scenarios

### Roadway Pavement Inventory and Condition Assessment

According to the 2040 USVI Comprehensive Transportation Master Plan, the condition of most of the roads in the Territory is fair to poor in St. Thomas and St. John, and good in St. Croix (Parsons Brinckerhoff). In St. Thomas and St. John, most roads are narrow, two lanes with no or narrow shoulders. Because of the topography, there are many blind corners. Pavement markings are mostly faded on many facilities, and guardrails are damaged or non-existent. These issues were confirmed by the community advisory groups for each island. This information is slightly outdated, but we do not have any updated information at the time of this study.

Below are the roadway pavement inventory condition maps we produced based on the 2017 ArcGIS dataset we collected. The present serviceability index (PSI) is based on the original AASHO Road Test PSR. PSI ranges from 5 (very good) to 0 (very poor).


Frenchmans Cay
Leinster Bay
Lovango Cay
Mingo Cay
Virgin Islands National Park
Hurricane Hole
St John
Mar Caribe
Caribbean Sea
Cruz Bay
Rendezvous Bay
367 m
403 m
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0 0.5 1mi
United States Virgin Islands, Esri, HERE, Garmin, INCREMENT P, USGS, METI/NASA, NGA

(a)


Magens Bay
Mahogany Run Golf Course
Thatch Cay
Caribbean Sea
Mar Caribe
Charlotte Amalie
St Thomas
Cyril E King International Airport
Virgin Islands National Park
Water Island
Great Bay
503 m
280 m
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0 0.5 1mi
United States Virgin Islands, Esri, HERE, Garmin, INCREMENT P, USGS, METI/NASA, NGA

(b)


Buck Island Reef National Monument
Christiansted
St Croix
Frederiksted
Kingshill
Henry E Rohlsen
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0 1 2mi
United States Virgin Islands, Kadaster Netherlands, Esri, HERE, Garmin, USGS, NGA

(c)

**Figure 16**: Colored pavement condition rating (PSI) of major roads in (a) St. John, (b) St. Thomas, and (c) St. Croix, USVI

### Roadway Intervention Scenarios

We define five pavement or roadway intervention scenarios based on the Pavement Treatment Triggers that identify ranges of pavement condition levels that should be used to select pavement preservation, minor rehabilitation, major rehabilitation, and reconstruction treatments. Typically, a road with a PSI of 0 - 1 has failed and would have to be reconstructed completely. The reconstructed PSI value would be a 5. A road with a PSI between 1 and 3 would be a candidate for various types of treatment and would raise the PSI level above 4.5. A road with a PSI between 3 and 4.5 would be a candidate for a pavement preservation treatment which would raise the PSI above 4.5.

Unit cost values are derived from the 2019 data in the USVI DPW Costing Table. The 1.5 PF values are multiplied by the material cost to estimate the installed cost. 10% annual escalation rate has been applied to estimate 2021 values.

**Table 5**: USVI Department of Public Works (DPW) Unit Cost Table

| Treatment | St. Croix ($/SY in 2021 value) | St. Thomas & St. John | Treatment Description |
|---|---|---|---|
| Reconstruction | $282 | $300 | |
| Major Rehabilitation | $100 | $194 | Mill/Functional Overlay (e.g., Mill 2"/Overlay 3") |
| Minor Rehabilitation | $73 | $150 | Mill/Structural Overlay (e.g., Mill 2"/Overlay 2") |
| Preservation | $31 | $50 | Thin overlay (e.g., Overlay 1") |

A map and bar chart displaying the distribution of pavement condition by PSI rating for the baseline scenario (Do Nothing) in St. Croix is presented as follows in

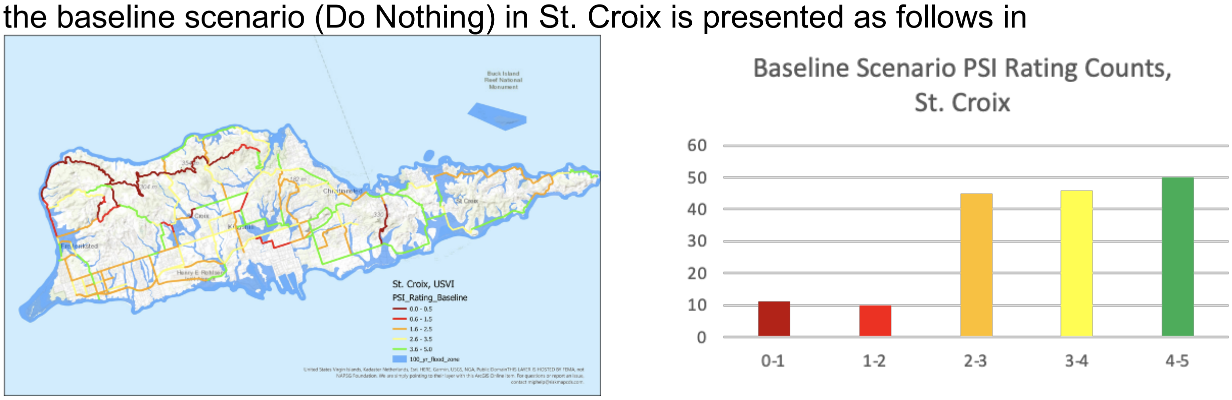
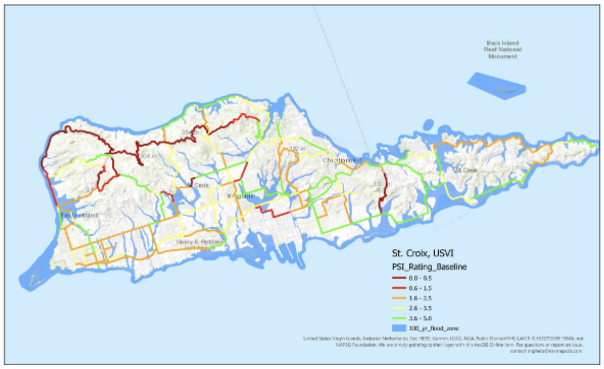



Figure 17. This represents the status quo scenario, which will be used later to compute the net cost and benefit of each treatment scenario across all islands of the USVI.



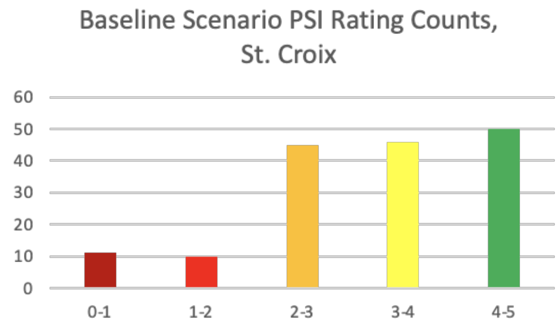




**Figure 17**: Pavement condition map and distribution for baseline scenario, St. Croix

We now define each of our five intervention scenarios by treatment type and triggering pavement condition thresholds, with maps and comparative bar charts provided for each in Figures Figure 18 through Figure 22.

**<u>Scenario 1</u>**

- Perform only reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise PSI to 5.

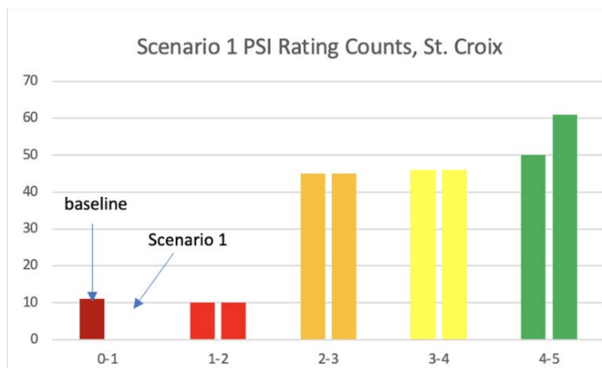




**Figure 18**: Pavement condition map and distributions for Scenario 1 compared to baseline, St. Croix

**<u>Scenario 2</u>**

- Perform reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise PSI to 5 and
- Major rehabilitation for all pavement between PSI rating 1-2 (1 and 1.5) to raise PSI to 5.

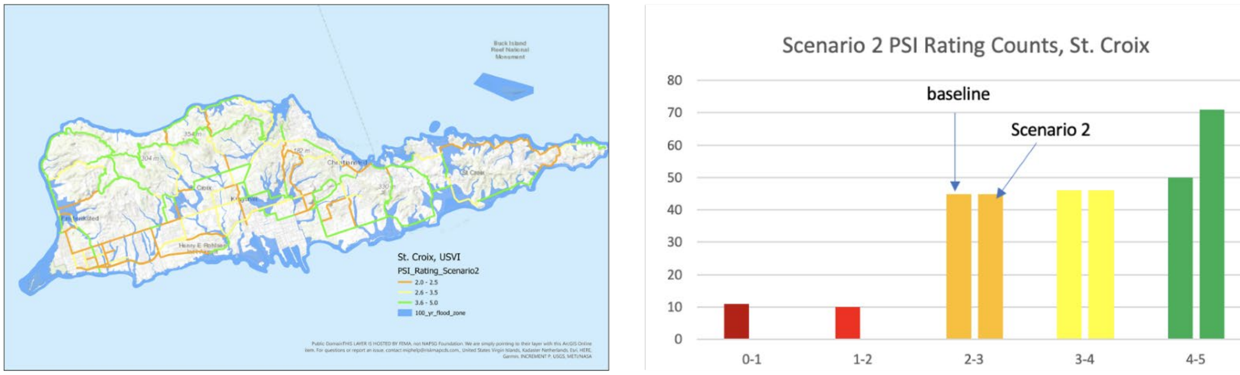



**Figure 19**: Pavement condition map and distributions for Scenario 2 compared to baseline, St. Croix

**<u>Scenario 3</u>**

- Perform reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise PSI to 5;
- Major rehabilitation for all pavement between PSI rating 1-2 (1 and 1.5) to raise PSI to 5; and
- Minor rehabilitation for all pavement between PSI rating 2-3 (2 and 2.5) to raise PSI to 5.

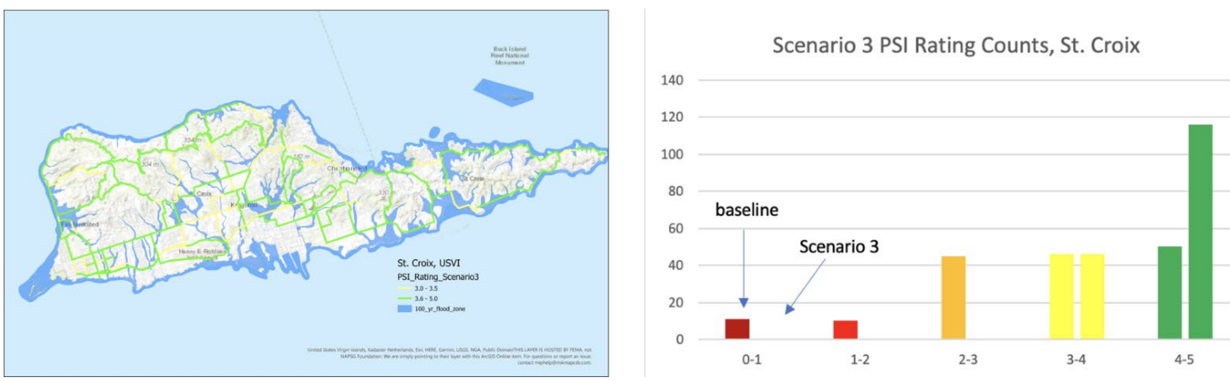



**Figure 20**: Pavement condition map and distributions for Scenario 3 compared to baseline, St. Croix

**<u>Scenario 4</u>**

- Perform reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise PSI to 5;
- Major rehabilitation for all pavement between PSI rating 1-2 (1 and 1.5) to raise PSI to 5;
- Minor rehabilitation for all pavement between PSI rating 2-3 (2 and 2.5) to raise PSI to 5; and
- Preservation for all pavement between PSI rating 3-4.5 (3, 3.5 and 4) to raise PSI to 5.

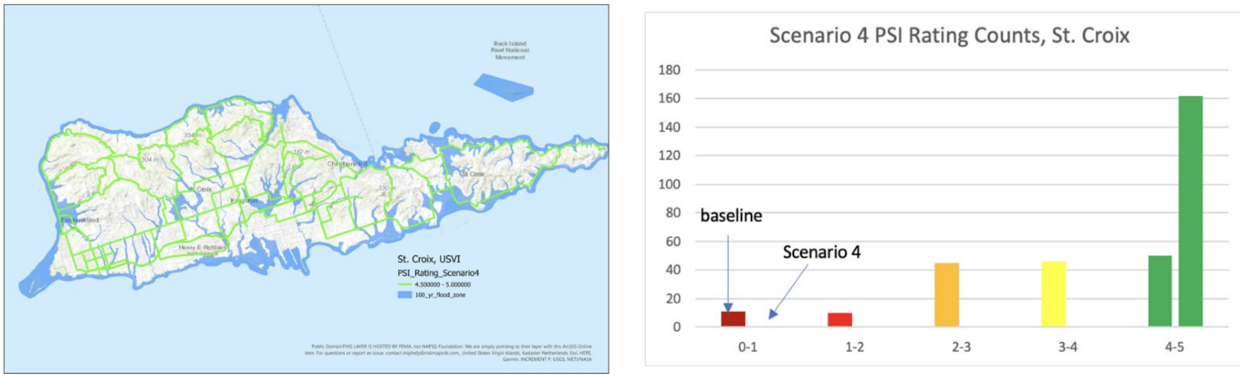



**Figure 21**: Pavement condition map and distributions for Scenario 4 compared to baseline, St. Croix

## Scenario 5

- Perform reconstruction for select, priority pavements under PSI rating 1 (0 and 0.5) to raise PSI to 5;
- Major rehabilitation for select, priority pavement between PSI rating 1-2 (1 and 1.5) to raise PSI to 5; and
- Minor rehabilitation for select, priority pavement between PSI rating 2-3 (2 and 2.5) to raise PSI to 5.

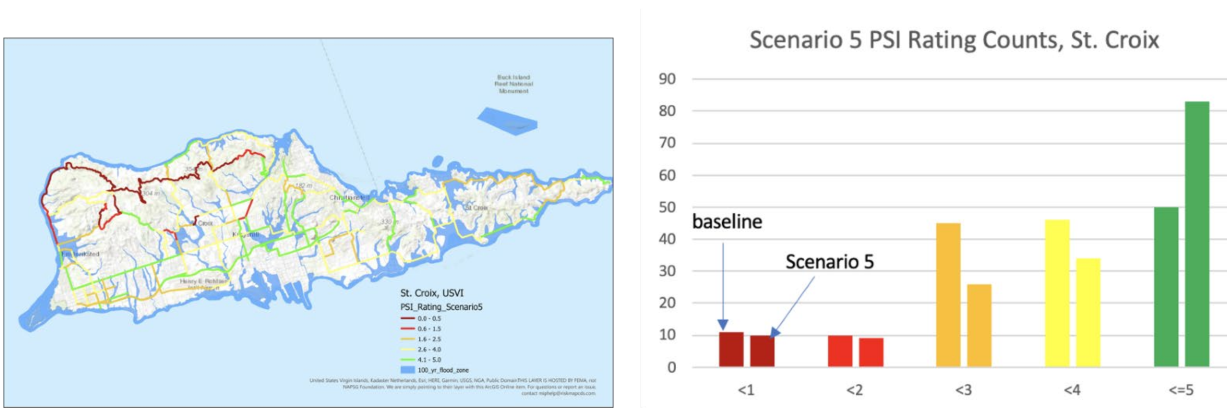



**Figure 22**: Pavement condition map and distributions for Scenario 5 compared to baseline, St. Croix

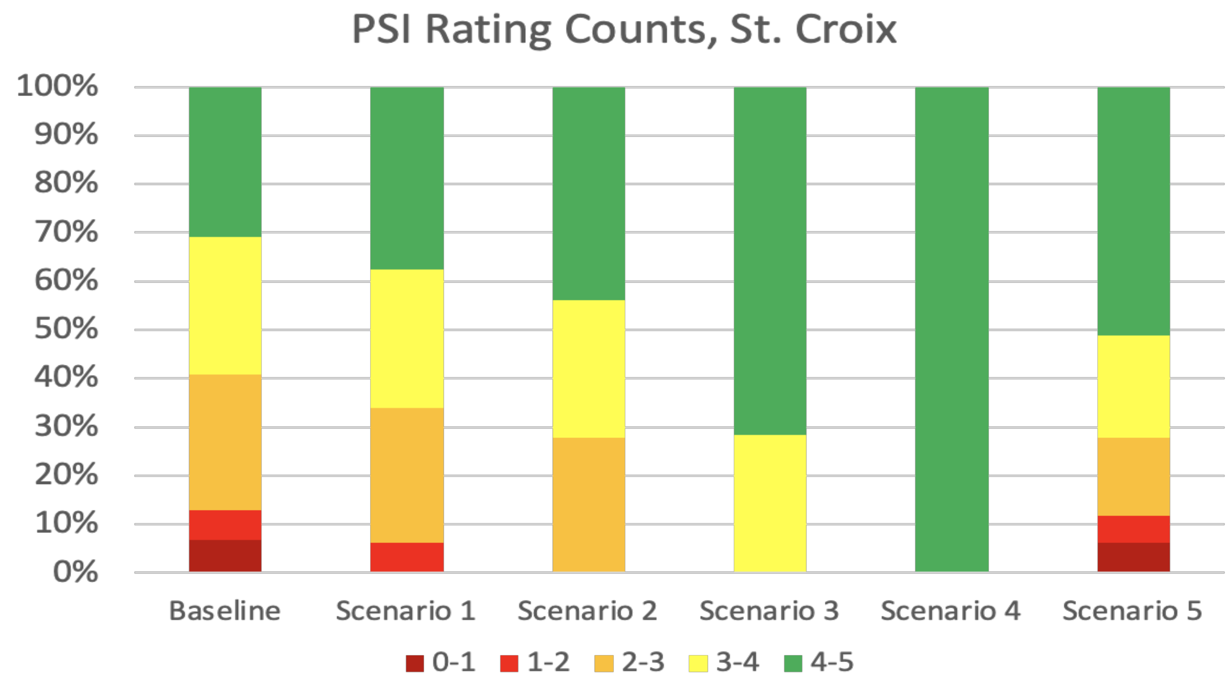



**Figure 23**: Pavement condition distribution by PSI rating compared across all scenarios, St. Croix

Table 6 illustrates which treatment actions are applied in each scenario, as well as which pavement sections were subjected to those treatment types by PSI level in each.

**Table 6**: Relationship between PSI, Types of Maintenance, and Scenarios

<table>
<tr><th>PSI</th><th>Type of Maintenance</th><th colspan="5">Scenario</th></tr>
<tr><td>0 & 0.5</td><td>Pavement Reconstruction</td><td>Scenario #1</td><td rowspan="2">Scenario #2</td><td rowspan="3">Scenario #3</td><td rowspan="4">Scenario #4</td><td rowspan="5">Scenario #5: PSI of 3 or less and above average usage</td></tr>
<tr><td>1 & 1.5</td><td>Major Pavement Rehabilitation</td><td></td></tr>
<tr><td>2 & 2.5</td><td>Minor Pavement Rehabilitation</td><td></td><td></td></tr>
<tr><td>3 & 3.5 & 4</td><td>Pavement Preservation</td><td></td><td></td><td></td></tr>
<tr><td>4.5 & 5</td><td>Do Nothing</td><td></td><td></td><td></td><td></td></tr>
</table>

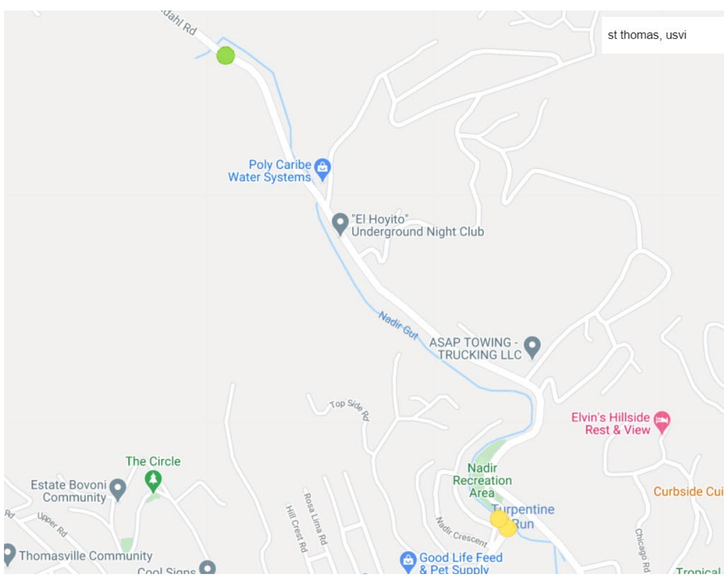
Note that we will consider only the one-time treatment action and short-term economic effects for roadway asset management analysis. Although it is possible to incorporate deterioration models to project into the long-term future to perform comprehensive life cycle cost analysis or network-level life cycle and capital planning, we will **not** develop or apply these long-term analyses in light of data limitations and to maintain simplicity in this illustrative case study.

## Bridge Inventory and Condition Assessment

Bridge inventory and condition data for USVI are extracted from the FHWA LTBP InfoBridge database, as displayed in Table 7. A data set of 24 bridges including 11 culverts are found in the database- 3 in St. Thomas and 21 in St. Croix- and contains 2020 NBI condition rating information. These bridges and culverts and their conditions, categorized by NBI rating as per Figure 7, are mapped in Figure 24.

**Table 7**: USVI Bridge (& Culvert) Inventory

| 1 - State Name | 8 - Structure Number | 22 - Owner Agency | 3 - County Name | 27 - Year Built | 29 - Average Daily Traffic | 43A - Main Design Mat Type Value | 43B - Main Construction Design Value | 45 - Number of Spans in Main Unit |
|---|---|---|---|---|---|---|---|---|
| '78 - Virgin Islands' | STX6991 | 'State Highway Agency' | '010' | 1910 | 300 | 'Masonry' | 'Culvert' | 3 |
| '78 - Virgin Islands' | STX8205 | 'State Highway Agency' | '010' | 1985 | 400 | 'Concrete' | 'Slab' | 1 |
| '78 - Virgin Islands' | SPRING GUT | 'State Highway Agency' | '010' | 1904 | 100 | 'Steel' | 'Girder and Floorbeam System' | 1 |
| '78 - Virgin Islands' | HESS CULVERT | 'State Highway Agency' | '010' | 1990 | 1000 | 'Concrete' | 'Culvert' | 2 |
| '78 - Virgin Islands' | STX7520 | 'State Highway Agency' | '010' | 2001 | 24 | 'Concrete' | 'Culvert' | 1 |
| '78 - Virgin Islands' | STX8001 | 'State Highway Agency' | '010' | 1990 | 100 | 'Concrete' | 'Culvert' | 3 |
| '78 - Virgin Islands' | STX6410 | 'State Highway Agency' | '010' | 1990 | 800 | 'Concrete' | 'Tee Beam' | 1 |
| '78 - Virgin Islands' | STX0001 | 'County Highway Agency' | '010' | 1980 | 1 | 'Concrete' | 'Culvert' | 2 |
| '78 - Virgin Islands' | STX6621 | 'State Highway Agency' | '010' | 1990 | 1500 | 'Concrete' | 'Tee Beam' | 1 |
| '78 - Virgin Islands' | STX6405 | 'State Highway Agency' | '010' | 1970 | 800 | 'Steel' | 'Stringer/Multi-beam or Girder' | 2 |
| '78 - Virgin Islands' | STX6620 | 'State Highway Agency' | '010' | 1990 | 1500 | 'Concrete' | 'Tee Beam' | 1 |
| '78 - Virgin Islands' | STX73205 | 'State Highway Agency' | '010' | 2006 | 300 | 'Prestressed Concrete' | 'Stringer/Multi-beam or Girder' | 5 |
| '78 - Virgin Islands' | STX7025 | 'State Highway Agency' | '010' | 1970 | 1000 | 'Concrete' | 'Tee Beam' | 1 |
| '78 - Virgin Islands' | STX65205 | 'State Highway Agency' | '010' | 1998 | 100 | 'Concrete' | 'Culvert' | 3 |
| '78 - Virgin Islands' | STX7310 | 'State Highway Agency' | '010' | 2006 | 120 | 'Concrete' | 'Slab' | 4 |
| '78 - Virgin Islands' | STX66905 | 'State Highway Agency' | '010' | 1990 | 120 | 'Concrete' | 'Frame' | 1 |
| '78 - Virgin Islands' | STX7020 | 'State Highway Agency' | '010' | 1910 | 1000 | 'Masonry' | 'Culvert' | 3 |
| '78 - Virgin Islands' | STX7215 | 'State Highway Agency' | '010' | 1920 | 300 | 'Concrete' | 'Frame' | 1 |
| '78 - Virgin Islands' | STX6611 | 'State Highway Agency' | '010' | 1985 | 1000 | 'Concrete' | 'Culvert' | 3 |
| '78 - Virgin Islands' | STX6610 | 'State Highway Agency' | '010' | 1985 | 1000 | 'Concrete' | 'Culvert' | 3 |
| '78 - Virgin Islands' | STX702505 | 'State Highway Agency' | '010' | 1927 | 400 | 'Concrete' | 'Stringer/Multi-beam or Girder' | 2 |
| '78 - Virgin Islands' | STT003 | 'State Highway Agency' | '110' | 1994 | 600 | 'Prestressed Concrete' | 'Box Beam or Girders - Multiple' | 3 |
| '78 - Virgin Islands' | STT005 | 'State Highway Agency' | '110' | 1985 | 500 | 'Concrete' | 'Culvert' | 2 |
| '78 - Virgin Islands' | STT007 | 'State Highway Agency' | '030' | 1985 | 500 | 'Concrete' | 'Culvert' | 2 |




(a)

(b)

**Figure 24**: Color-coded conditions and locations of (a) the 3 bridges on St. Thomas and (b) the 21 bridges on St. Croix

(Key: Red – Poor, Yellow – Fair, Green – Good)

### Bridge Intervention Criteria

Based on typical bridge intervention criteria, we assume that replacement only applies to the bridges at NBI rating 4 and retrofit and preservation apply to bridges at ratings 5-7. The unit costs are derived from FHWA website for Puerto Rico, and the preliminary unit cost of replacement is $246/ft$^2$, major rehabilitation $67/ft$^2$, and preservation or minor maintenance $60/ft$^2$.

## 3.3 Infrastructure Asset Management (Under Normal Condition)

To assess bridge how much a bridge's conditions will deteriorate over time, the Health Index model below is applied. In this model, as shown in Equations 2, $C_i$ is the initial condition, $a_n$ is the slope of deterioration, and $S_i$ is the current year of service life. c is the deterioration power exponent, which is an empirical, constant value derived from a sensitivity analysis. Finally, $C_f$ is the final condition, where the early-warning level is seen, and $S_f$ is the assumed final year of service life.

$$C_i(t) = C_I + a_n \cdot (S_i - S_I)^c$$

$$C_i(t) = a_n \cdot \left( \sqrt[c]{\frac{C_{i-1}}{a_n}} + 1 \right)^c$$

$$a_n = (C_F - C_I) / (S_F - S_I)^c$$

**Equations 2**: Health index model equations for aging structural condition (Veit-Egerer, Robert & Wenzel, Helmut & Lima, Rui, 2013)

### Bridge Intervention Scenarios

The health index deterioration model from Equations 2 is plotted for each of 4 bridge scenarios or cases over 75 years, with interventions for each described in Figures Figure 25 through Figure 28.

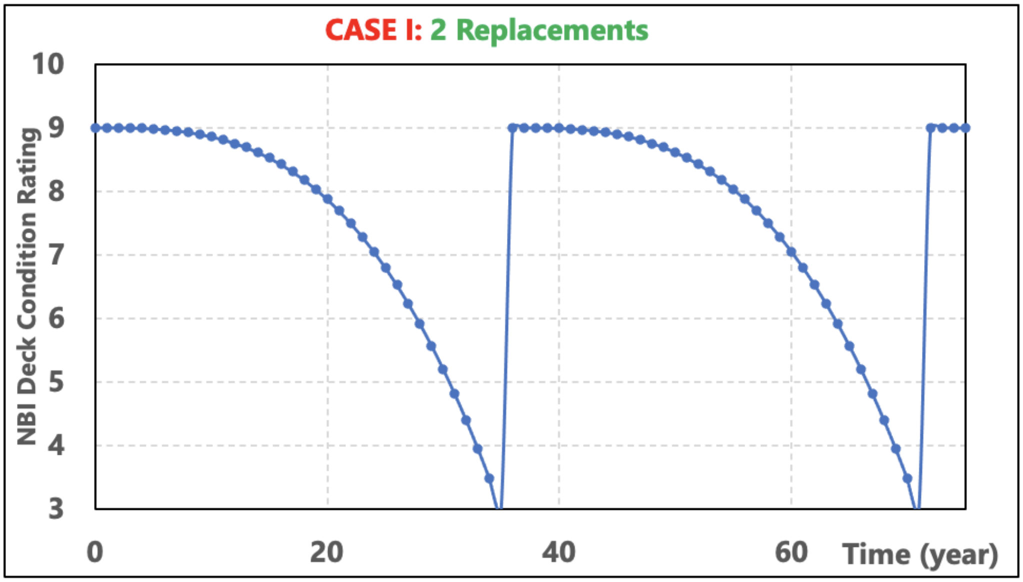



**Figure 25**: Bridge intervention modeling for Case 1. Consists of 2 Replacement treatments, with the first one after approximately 37 years and the second after around 67 years.

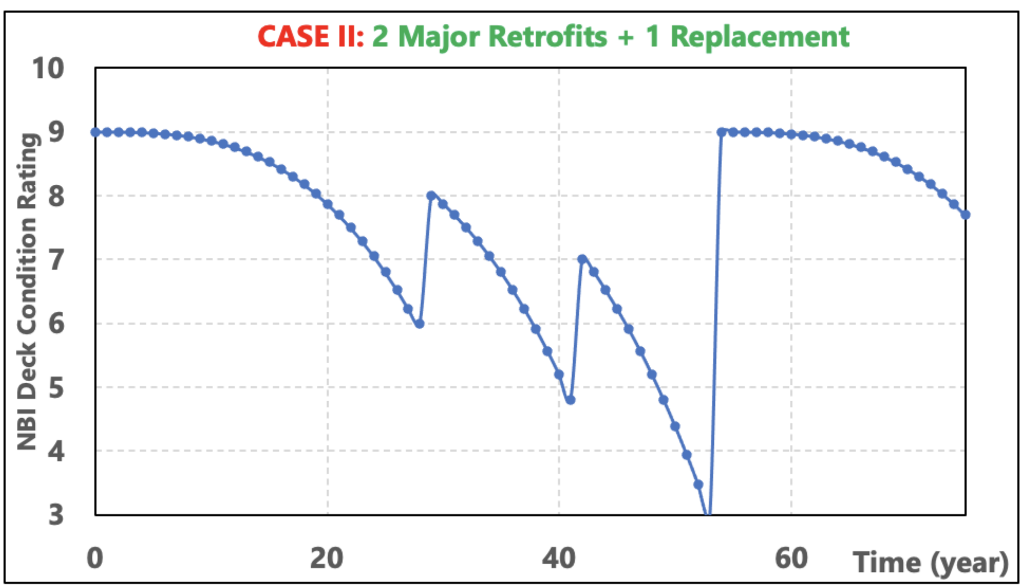


**Figure 26**: Bridge intervention modeling for Case 2. Consists of 2 Major Retrofits (around 25 and 41 years after the bridge was built) and 1 Replacement (55 years).

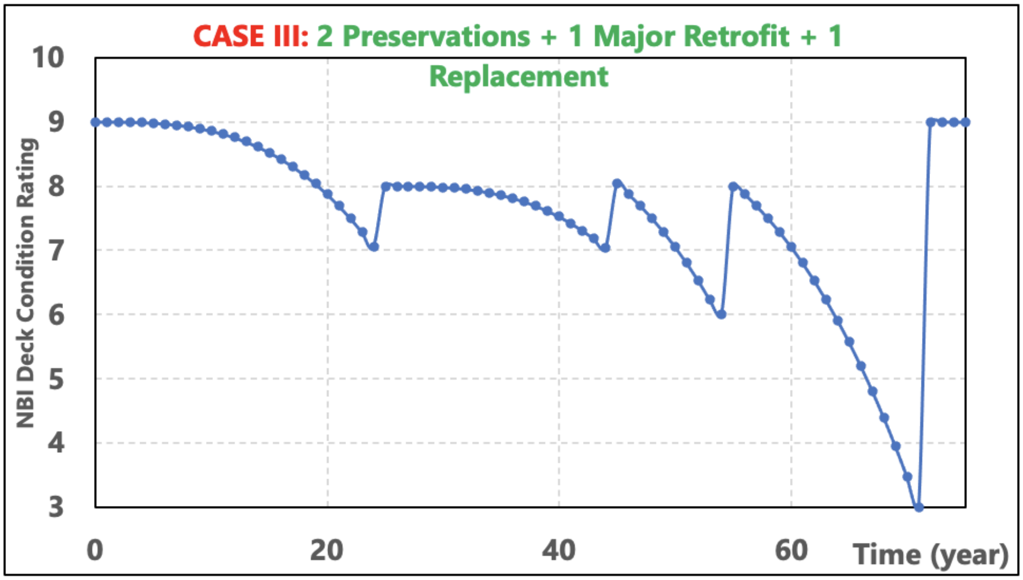



**Figure 27**: Bridge intervention modeling for Case 3. Consists of 2 Preservations (approximately 25 and 43 years after the bridge was built), 1 Major Retrofit (55 years), and 1 Replacement (70 years).

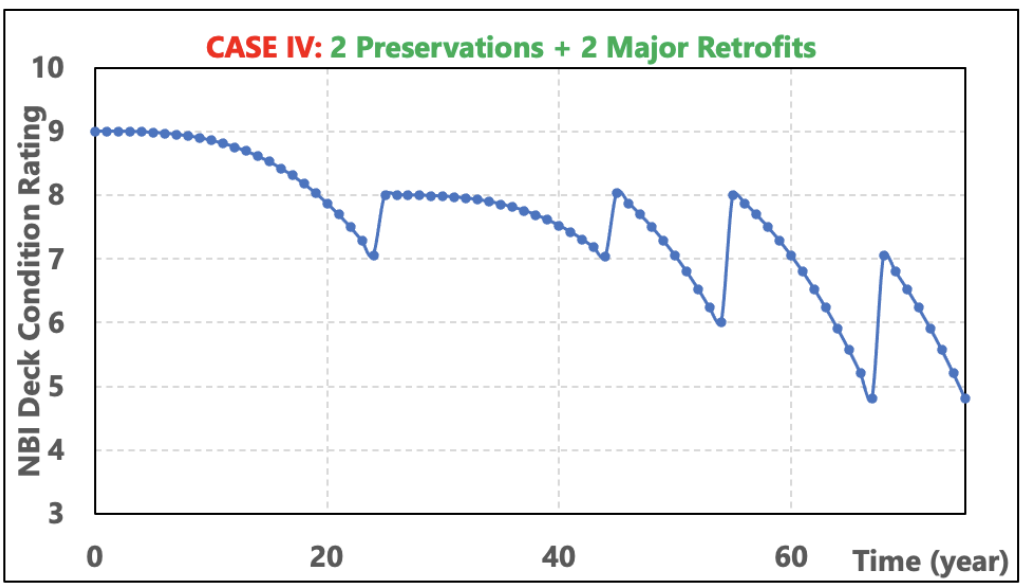



**Figure 28**: Bridge intervention modeling for Case 4. Consists of 2 Preservations (around 20 and 40 years after building) and 2 Major Retrofits (55 and 65 years).

For each intervention case, we calculated the costs of the treatments involved to produce a life-cycle cost. As shown in Table 8, Case 4 involved the lowest projected life cycle cost, despite involving four treatments over the 75-year time period (versus two treatments each in Cases 1 and 2).

**Table 8**: 75-year Life-Cycle Costs for a Bridge with 2000 sq. ft. of Deck Area

| Scenario Case | Actions | Life Cycle Costs * |
|---|---|---|
| Case I | 2 Replacements | $984,000 |
| Case II | 2 Major Retrofits | $1,160,000 |
| Case III | 2 Preservations + 1 Major Retrofit + 1 Replacement | $1,066,000 |
| Case IV | 2 Preservations + 2 Major Retrofits | $908,000 |

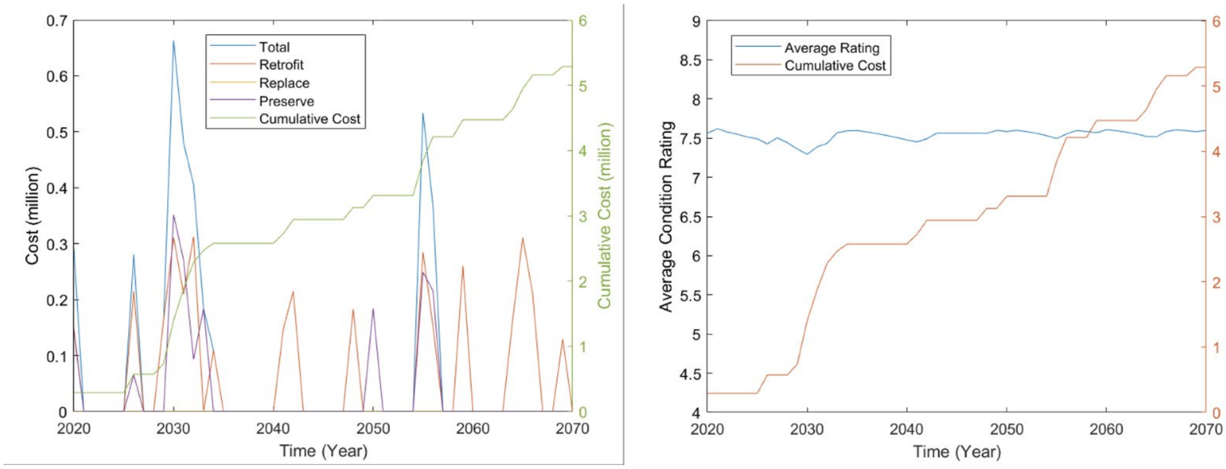
** Limited to agency costs*

### Network-Level Bridge Assessment

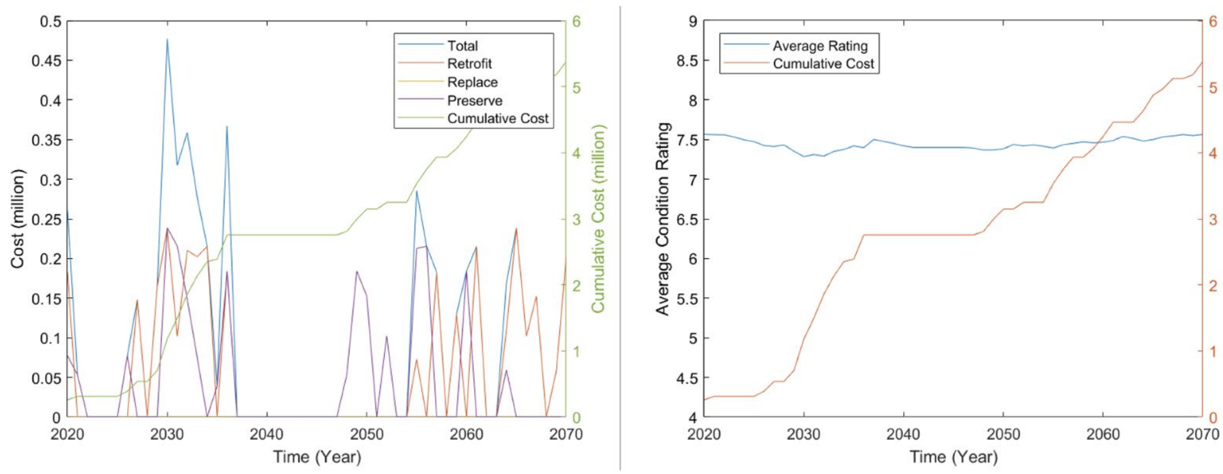
While the bridge intervention scenarios evaluate individual bridges, the network-level bridge assessment will analyze a set of bridges, which will have a total budget constraint. This is more realistic for agencies because it takes on a holistic view as to how to maximize the total benefits. We applied a customized heuristic algorithm to optimize the allocation of budget among bridges and the intervention actions in each year across a 50-year planning horizon.

The assumptions for a network-level assessment include: 1) replacement is not included as it is often conducted by the capital project allocation, not the annual MR&R budget; 2) Puerto Rico unit costs (reported by the FHWA) are used for calculation, in order to produce relevant findings for the USVI as a fellow U.S. island territory; 3) an unlimited budget scenario assumes no annual budget cap for any MR&R action; 4) limited budget scenarios, which are more realistic, assume an annual budget cap for the combination of MR&R actions; 5) leftover budget does not transfer to the next year; and 6) the average condition rating is the weighted average of bridges based on deck areas.

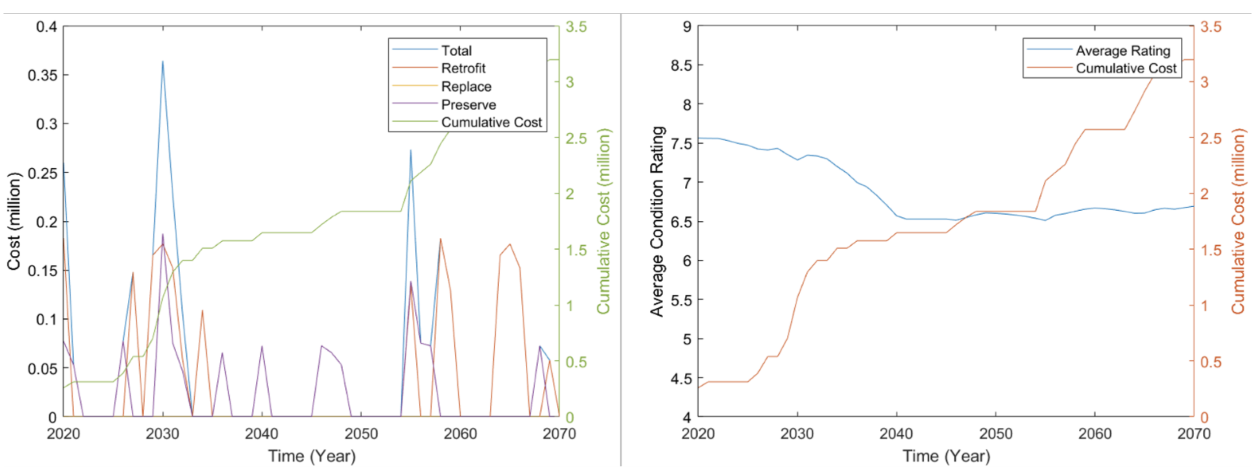
Between the following five network-level bridge intervention scenarios in Figure 29, the only difference is the total budget provided for the system. Each case follows 50% major retrofits and 50% preservation and does not utilize replacement.


Total
Retrofit
Replace
Preserve
Cumulative Cost
Cost (million)
Cumulative Cost (million)
Time (Year)
Average Rating
Cumulative Cost
Average Condition Rating
Cumulative Cost (million)
Time (Year)

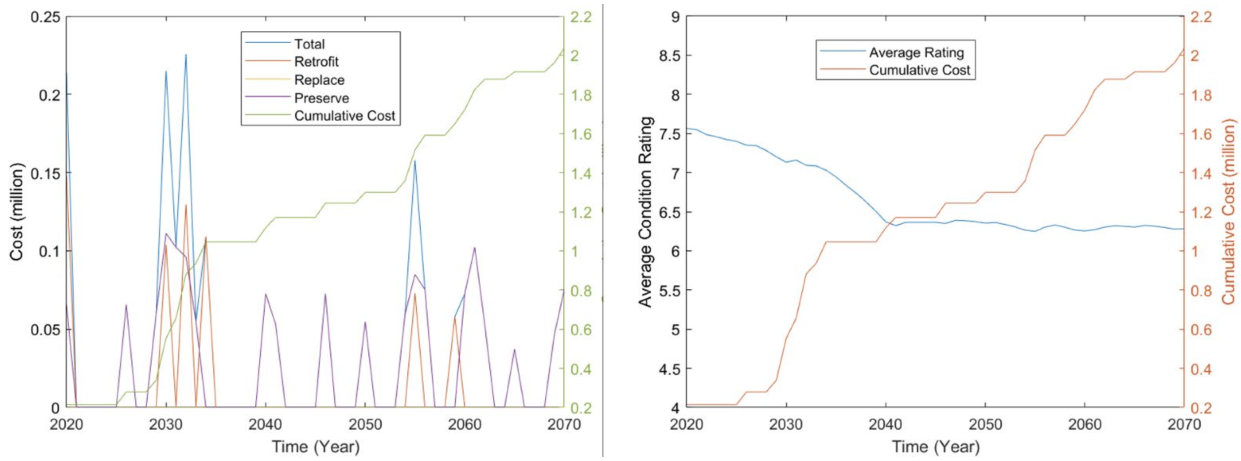
(a)


Total
Retrofit
Replace
Preserve
Cumulative Cost
Cost (million)
Cumulative Cost (million)
Time (Year)
Average Rating
Cumulative Cost
Average Condition Rating
Cumulative Cost (million)
Time (Year)

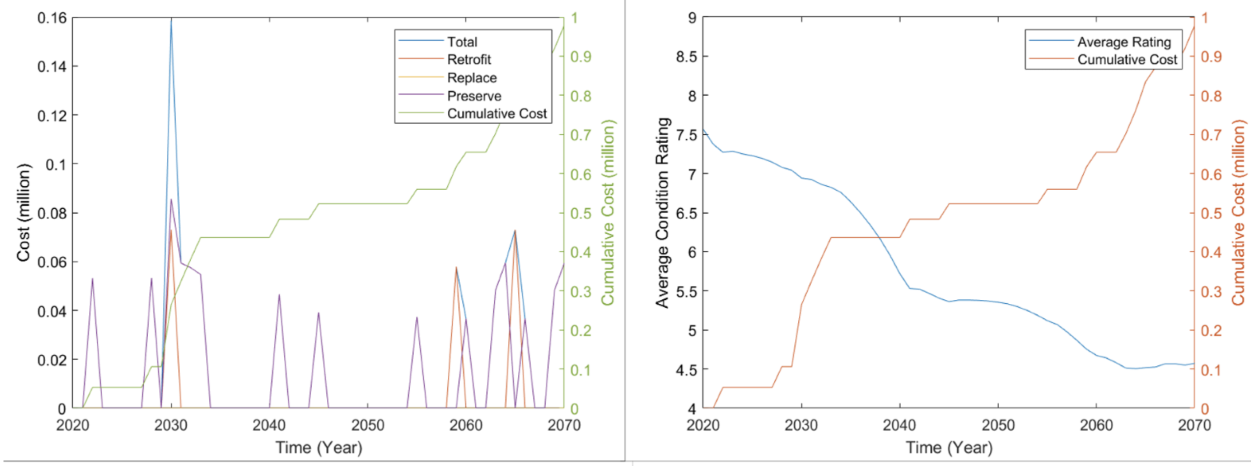
(b)


Total
Retrofit
Replace
Preserve
Cumulative Cost
Cost (million)
Cumulative Cost (million)
Time (Year)
Average Rating
Cumulative Cost
Average Condition Rating
Cumulative Cost (million)
Time (Year)

(c)




(d)




(e)

**Figure 29**: Network-level bridge intervention costs and condition ratings for (a) Scenario 1, limited \$1 million annual budget; (b) Scenario 2, limited \$0.5 million annual budget; (c) Scenario 3, limited \$0.4 million annual budget; (d) Scenario 4, limited \$0.3 million annual budget; and (e) Scenario 5, limited \$0.2 million annual budget. All interventions included no Replacement needed, Retrofit 50%, Preservation 50%.

For each network-level intervention scenario, we calculated a cumulative cost for the Retrofit and Preservation treatments across the 50-year period with the assumptions established earlier in mind. Table 9 shows these cumulative costs as well as the average condition rating for bridges in the system after 50 years, given each scenario's annual budget limit. We found the most efficient funding scenario at a \$400K annual budget, where the average bridge rating (for the entire inventory) stays at 6.6 with a cumulative 50-yr cost of \$3.2 million (\$65K /year).

**Table 9**: Summary of 50-year Network-Level Life Cycle Costs for USVI's Bridge Inventory

| Type of Case | Annual Budget Limit ($) | Actions | 50-yr Cumulative Costs (million $) | 50-yr Average Condition Rating |
|---|---|---|---|---|
| MR&R | 1M | Retrofit 50%, Preservation 50% | 5.25 | 7.6 |
| | 500K | Retrofit 50%, Preservation 50% | 5.25 | 7.5 |
| | 400K | Retrofit 50%, Preservation 50% | 3.2 | 6.6 |
| | 300K | Retrofit 50%, Preservation 50% | 2.0 | 6.2 |
| | 200K | Retrofit 50%, Preservation 50% | 1.0 | 4.5 |

In summary, the roadway pavement and bridge analyses in this section illustrate how asset management analysis could be applied to determine the optimal MR&R, budget and infrastructure investment strategies under normal condition. For short term when the impact of life cycle cost is not considered (the roadway pavement example), notable improvement of roadway condition requires significant investment, but will have a direct, timely impact on the overall infrastructure performance and risk profile. In the next sections, we will show the cost and benefit of different scenarios in terms of risk and economic impact. For long term when deterioration and LCC are of concern (the bridge example), asset management analysis can predict the infrastructure condition under different long-term intervention and investment scenarios and determines the best strategy by optimization. These will also affect the long-term system risk considering extreme situations and broad economic impact, which should be incorporated in decision-making.

## 3.4 Risk and Resilience Analysis

In the previous section, we demonstrated how asset management procedures are used to assess how much a bridge's condition will deteriorate over time under normal conditions. Once initial condition, slope or rate of deterioration, and final condition have been calculated using the Health Index model, all values are used in calculations under for alternative maintenance scenarios and intervention scenarios, to determine the extent to which an asset can be rehabilitated.

Our risk assessment methods, which add on extreme condition contributions and risk by cost, are applied here to two roadway segments on St. Island in the USVI. We present the detailed process to calculate these values for the example segments to illustrate the implementation of analytical frameworks in 3.4.1, followed by the network results for all five scenarios defined in 3.4.2.

### Facility-Level Risk Assessment

Facility-level risk assessment requires us to collect more detailed information about facilities and use this data to calculate risk and resilience measures.

The roads in USVI were aggregated into numerous segments for transportation agencies to conduct a risk analysis on. For this case study, we will apply the CDOT method (based on the ASME's RAMCAP approach) as a quantitative method to calculate for monetized risk and resilience measures ($/year), then present the USDOT VAST Approach as an alternative approach in this section.

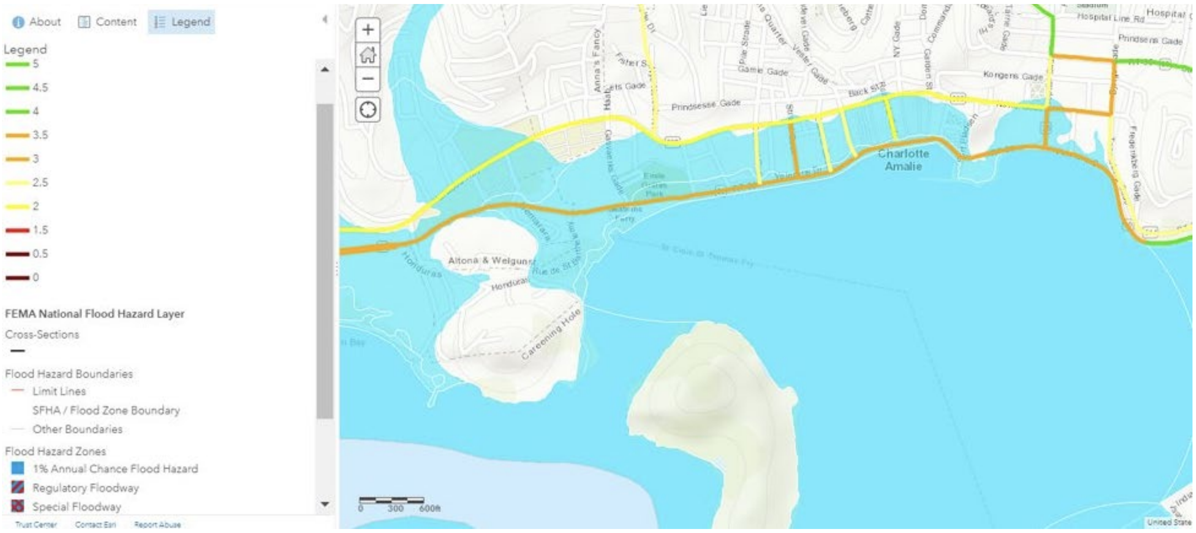
#### *3.4.1.1 CDOT & RAMCAP Based Method*

**Step 1: Study Scope & Asset Characterization**

The two main road segments that were selected as representative examples for illustrating our risk assessment procedures were Route 30 (Veterans Drive) and Route 32 (Turnpike), which encompass the scope of this risk analysis case study.

Segment 1, USVI Route 30 (Veterans Drive), lies close to the coast of Charlotte Amalie, St. Thomas. It is a 1.4 mile stretch of 4-lane highway that runs between an international airport and a medical center. Its AADT for vehicles is 16,230 (vehicles/day) and AADT for trucks are 2,160 (trucks/day). Thus, this segment of Route 30 is a crucial, highly trafficked roadway. Since nearly all of Segment 1 lies within the 100-year FEMA National Flood Hazard Layer (NFHL) flood zone, it is at high risk for coastal flooding. Its Soil Type is USDA UbD UcC (Urban Land), short for Urban Land-Cinnamon Bay Complex (0-12% slopes), and its Average Elevation is 1.58 meters, both of which mean that the chosen road segment is occasionally flooded. Its pavement condition rating PSI was 3.0 (good).

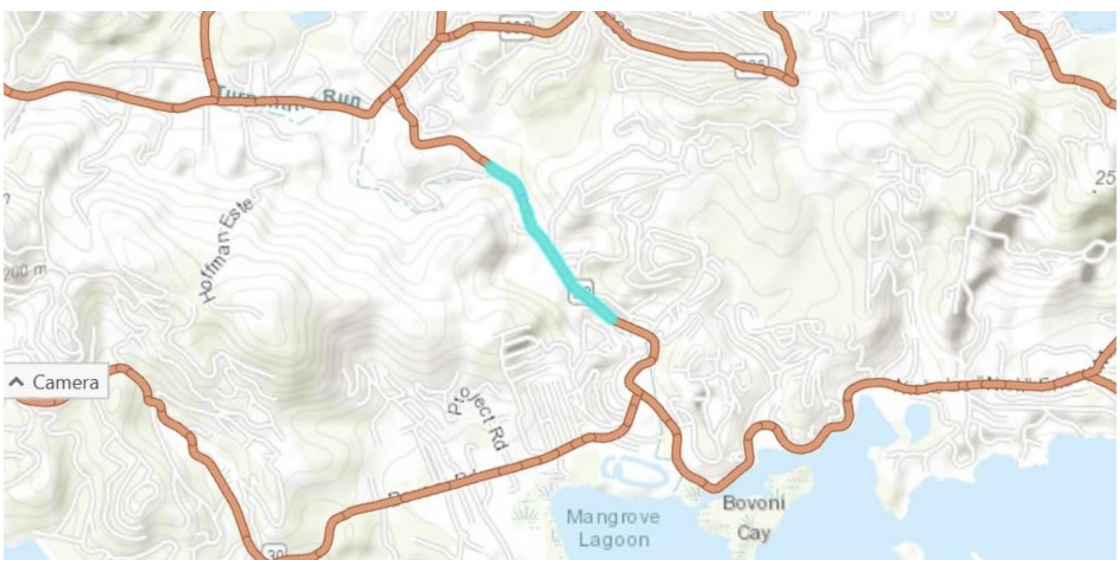

(a)



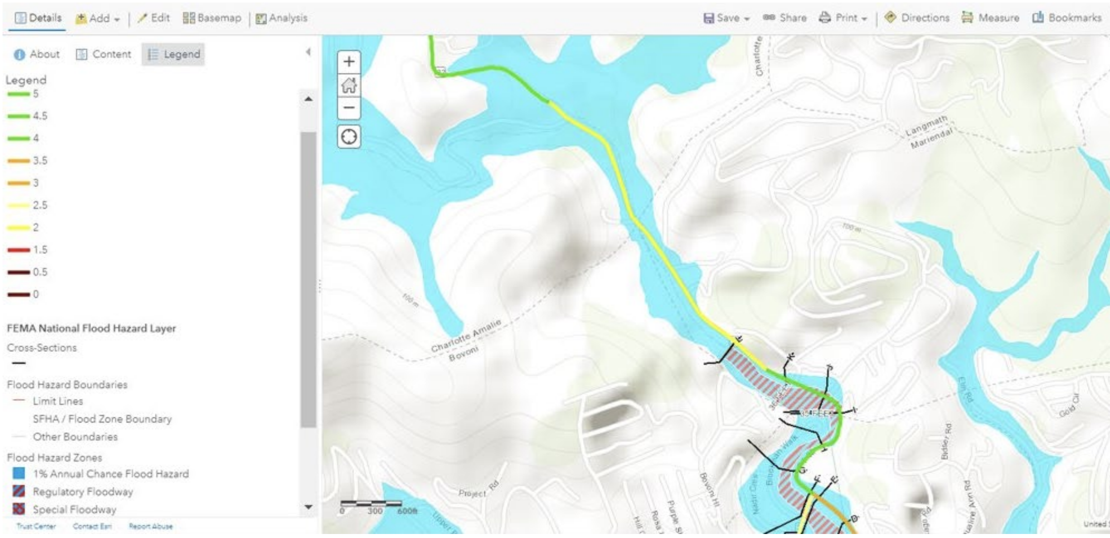

(b)

**Figure 30**: Segment 1, Route 30 (Veterans Drive) (a) highlighted on road map and (b) overlayed on FEMA NFHL map

Segment 2 is Route 32/Turpentine Run Road, St. Thomas, a 0.61 mile stretch of 2-lane highway that also lies in Charlotte Amalie, specifically northwest of Compass Point Marina. The AADT for vehicles is 8,400 (vehicles/day), and the AADT for trucks is 6,300 (trucks/day). Similar to Segment 1 (Veterans Drive), all of the chosen segment of Route 32 lies within the FEMA NFHL 100-year flood zone, so it is also at high risk for coastal flooding. Its Soil Type is USDA SrD, short for Southgate-Rock outcrop complex (12-20% slopes), and its Average Elevation is 17.5 m, both of which mean that they are occasionally flooded. Its Pavement Condition rating is 2.0 (fair) given its measurements.




(a)




(b)

**Figure 31**: Segment 2, Route 32 (Turpentine Road) (a) highlighted on road map and (b) overlayed on FEMA NFHL map

**Step 2: Threat Characterization**

The threat scenario being considered is a 100-year coastal flood (1% probability) for both road segments. Based on the chosen segments in the FEMA NFHL, 1.4 miles of Route 30 and 0.61 miles of Road 32 lie within the affected areas of this hazard.


**Figure 32**: FEMA NFHL map expanded for Segment 1, Route 30 (Veterans Drive)

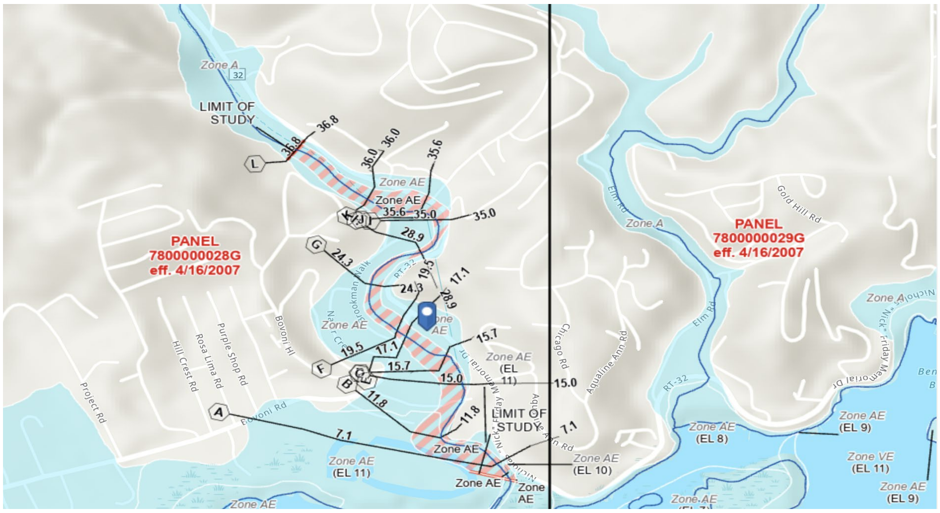


**Figure 33**: FEMA NFHL map expanded for Segment 2, Route 32 (Turpentine Run Road)

**Step 3: Consequence Analysis**
The consequences are the total owner consequence, total user consequence, annual owner risk, and annual user risk. The total Annual Owner Risk is calculated by multiplying the Owner Consequence with Vulnerability and Threat Likelihood. The total Annual User Risk is calculated by multiplying User Consequence with Vulnerability and Threat Likelihood.

The following data is required to calculate Owner and User Consequence for both road segments:

- Unit Replacement Cost ($/yard)
- Clean Up Cost ($)
- Road Surface Area (yard$^2$/mile)
- Number of Full Closure Days (days)
- $AADT_{Vehicle}$ (vehicles/days)
- $AADT_{Truck}$ (trucks/days)
- Truck Speed (miles/hour)
- Average Vehicle Occupancy (people/vehicle)
- Car Running Cost ($/vehicle-mile)
- Truck Running Cost ($/vehicle-mile)
- Detour Distance (miles, minutes)

Owner Consequence is calculated with the following Equation 3 suggested in the CDOT 2020 *Risk & Resilience Analysis Procedure*:

Owner Consequence ($) = Replacement Cost ($) = Owner Unit Cost ($/yard$^2$) * Road Area (yard$^2$/mile) * Road Length (miles) + Clean Up Cost ($)

**Equation 3**: CDOT Method owner risk consequence calculation

User Consequence is calculated with the following Equation 4 suggested in the CDOT 2020 *Risk & Resilience Analysis Procedure*:

$$\text{User Consequence (\$)} = (\text{Car Running Cost (\$/vehicle-mile)} * AADT_{Vehicle}\ \text{(vehicles/day)} + \text{Truck Running Cost (\$/truck-mile)} * AADT_{Truck}\ \text{(trucks/day)} * \text{Number of Full Closure Days (days)} * (\text{Detour Route Length (miles)} - \text{Original Route Length (miles)})$$

**Equation 4**: CDOT Method user risk consequence calculation

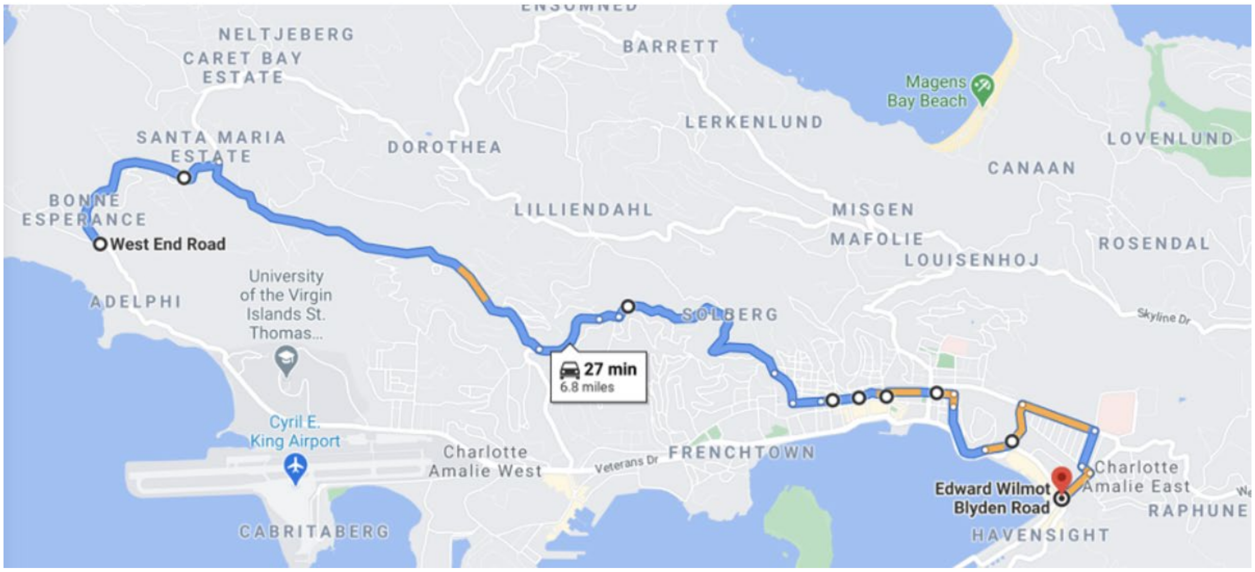



**Figure 34**: Sample Segment 1/Route 30 detour route (Google Maps, 2021)

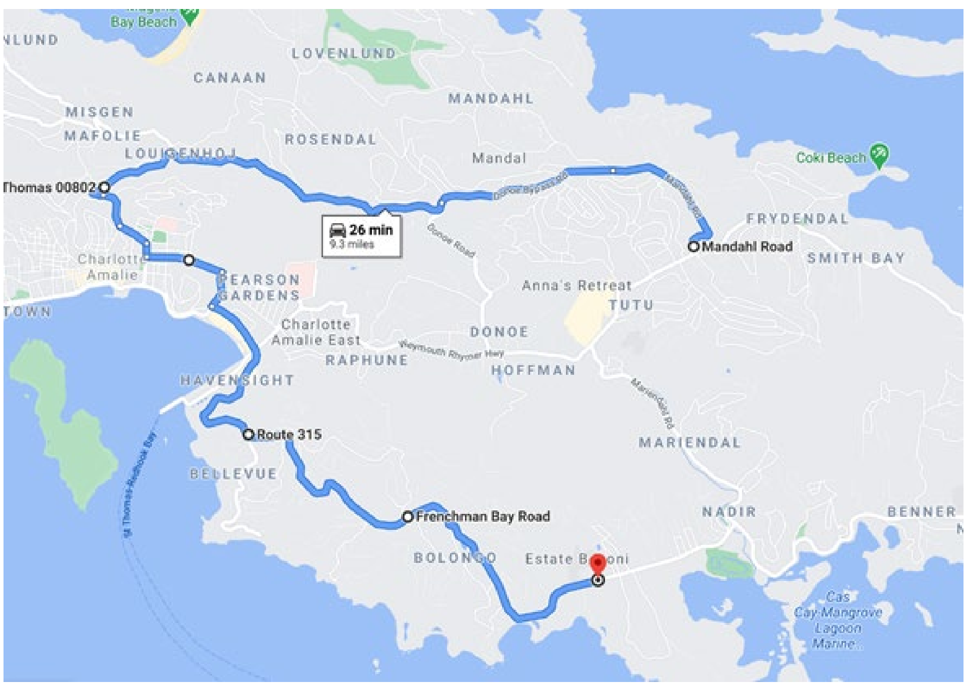


**Figure 35**: Sample Segment 2/Route 32 detour route (Google Maps, 2021)

**Step 4: Vulnerability Analysis**
In this context, vulnerability is referenced based on soil type, terrain, and pavement ratings of road segments. Since the temperature in St. Thomas is consistently above freezing, the Frost Action for this region is categorized as "None." We incorporated pavement condition rating and soil type in determining embankment erodibility based on expert elicitation (Table 10). The soil data we obtained is USDA classification. We further developed a conversion table to convert based on the composition of sand, silt and clay into three main AASHTO classes A1-A3, A4-A8 and Unknown. Segment 1, Route 30 has USDA UbD UcC (Urban Land) soil, which is classified as unknown category; with a PSI condition rating 3, its embankment erodibility is moderate. Segment 2, Route 32 has USDA SrD soil, which is classified as A4-A8 AASHTO category; with a PSI condition rating 2, its embankment erodibility is high.

**Table 10**: Embankment Erodibility Table

| Soil Class | Pavement Condition Rating | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5 | 4.5 | 4 | 3.5 | 3 | 2.5 | 2 | 1.5 | 1 | 0.5 | 0 |
| A1-A3 | Very Low | Very Low | Very Low | Low | Low | Low | Low | Moderate | Moderate | Moderate | Moderate |
| A4-A8 | Moderate | Moderate | Moderate | High | High | High | High | Very High | Very High | Very High | Very High |
| Unknown | Low | Low | Low | Moderate | Moderate | Moderate | Moderate | High | High | High | High |

Then the vulnerability index, indicating the probability of damage when a flood event occurs in this context, can be estimated based on the following table which was developed in the CDOT manual.

**Table 11:** Roadway Prism Vulnerability for 100-Year and 500-Year Flood Events (CDOT, 2020, p. 108)

| Flood Event | Terrain | Embankment Erodibility Potential | | | | |
|---|---|---|---|---|---|---|
| | | Very Low | Low | Moderate | High | Very High |
| 100-yr | Level | 0.22 | 0.23 | 0.25 | 0.31 | 0.33 |
| | Rolling | 0.26 | 0.28 | 0.3 | 0.36 | 0.39 |
| | Mountainous | 0.35 | 0.37 | 0.4 | 0.48 | 0.52 |
| 500-yr | Level | 0.55 | 0.59 | 0.63 | 0.77 | 0.83 |
| | Rolling | 0.66 | 0.70 | 0.75 | 0.91 | 0.99 |
| | Mountainous | 0.88 | 0.93 | 0.99 | 0.99 | 0.99 |

The terrain for both road segments (based on the slope) is "Level". With the embankment erodibility and 100-year flood category, the vulnerability values for the two segments are 0.25 and 0.31 respectively.

**Steps 5 & 6: Risk/Resilience Assessment and Management**

This step involves deciding whether the calculated risk and resilience levels for each threat/asset combination are financially acceptable or reasonable. If not, we need to determine the optimal countermeasures and mitigation strategies to implement, all of which need to be evaluated by recalculating the risk and resilience of the threat/asset combinations under the assumption each strategy has been implemented and then comparing the results. Then, the agency should implement the best strategies and create a plan for continuous monitoring and evaluation ("All Hazard Risk & Resilience," 2009). For every plan, there is a specific type of action correlated with an assumed specific treatment.

The following tables are full calculations of owner and user risk values (costs) on our case study Segments 1 and 2, factoring in the equations and considerations determined for consequences and vulnerability of these roadways in Step 3 and 4.

**Table 12**: CDOT Method Annual Owner and User Risk Calculations for USVI Segments

| | **Route 30 (Veterans Drive)** | **Route 32/Turpentine Run Rd** |
|---|---|---|
| Threat Likelihood | 0.01 (100-Year Flood) | 0.01 (100-Year Flood) |
| Vulnerability* | 0.25 | 0.31 |
| Consequence | Total Owner Consequence = $13,803,400<br>Total User Consequence =$383,014 | Total Owner Consequence = $3,001,080<br>Total User Consequence =$562,652 |
| **Annual Owner Risk (expected owner cost)** | Owner Consequence x Vulnerability x Threat Likelihood = $30,845/Year | Owner Consequence x Vulnerability x Threat Likelihood = $8,332/Year |
| **Annual User Risk** | User Consequence x Vulnerability x Threat Likelihood = $958/Year | User Consequence x Vulnerability x Threat Likelihood = $1,744/Year |

**Table 13**: CDOT Method User Consequence Calculations for USVI Segments

| | **Route 30 (Veterans Drive)** | **Route 32/Turpentine Run Rd** |
|---|---|---|
| User Consequence parameters | Number of Full Closure Days: 3 (days)<br>$AADT_{Vehicle}$ = 16,230 (vehicle/day)<br>$AADT_{Truck}$ = 2,161 (truck/day)<br>Detour Distance = 6.8 miles, 27 minutes<br>Truck Speed = 30 (mi/hour) | Number of Full Closure Days: 3 (days)<br>$AADT_{Vehicle}$ = 8,400 (vehicle/day)<br>$AADT_{Truck}$ = 6,300 (truck/day)<br>Detour Distance = 9.3 miles, 26 minutes<br>Truck Speed = 30 (mi/hour) |

| | | |
|---|---|---|
| | Average Vehicle Occupancy = 1.77 (people/vehicle)<br>Car Running Cost = 0.59 (\$/vehicle-mile)<br>Truck Running Cost = 0.96 (\$/truck-mile)<br>Average Value of Time = 10.62 (\$/Adult-Hour)<br>Average Value of Freight Driver Cost = 25.31 (\$/Truck-Hour) | |
| User Consequence 1 - Vehicle Operating Cost (VOC) | (Car Running Cost x $AADT_{Vehicle}$ + Truck Running Cost x $AADT_{Truck}$)x Number of Full Closure Days x (Detour Route Length - Original Route Length) = \$188,734 | (Car Running Cost x $AADT_{Vehicle}$ + Truck Running Cost x $AADT_{Truck}$)x Number of Full Closure Days x (Detour Route Length - Original Route Length) = \$286,874 |
| User Consequence 2 – Lost Wage (LW) | (Average Value of Time * Average Occupancy * AADT + Average Value of Freight Time * AADTT) * Number of Full Closure Days * Extra Travel Time = \$194,279 | (Average Value of Time * Average Occupancy * AADT + Average Value of Freight Time * AADTT) * Number of Full Closure Days * Extra Travel Time = \$275,778 |

**Table 14**: CDOT Method Owner Consequence Calculations for USVI Segments

| | **Route 30 (Veterans Drive)** | **Route 32/Turpentine Run Rd** |
|---|---|---|
| Owner Consequence Parameters | Number of Lanes: 4<br>Inundated Length = 1.4 (mile)<br>Road Surface Area: 28,160 ($yard^2$/mile) | Number of Lanes: 2<br>Inundated Length = 0.61 (mile)<br>Road Surface Area: 14,080 ($yard^2$/mile) |
| | Owner Unit Cost: 300 (\$/$yard^2$) in St. Thomas *<br>Clean Up Cost: 2.71 (\$/$yard^2$) in St. Thomas *<br>Roadway area per lane mile: 7,040 (SY/lane-mile) | |
| Owner Consequence | = Replacement Cost = Owner Unit Cost * Road Area per Mile * Inundated Road Length (miles) = \$ 11,934,055 | = Replacement Cost = Owner Unit Cost * Road Area per Mile * Inundated Length (miles) = \$ 2,599,919 |

On Route 30 (Segment 1), the Annual Owner Risk was \$30,845/year and the Annual User Risk was \$958/year. On Route 32 (Segment 2), the Annual Owner Risk was \$8332/year, and the Annual User Risk was \$1774/year. Between the two road segments, the consequence analysis concludes that Route 30 has the higher Annual Owner Risk, while Route 32 has the higher Annual User Risk.

### *3.4.1.2 An Alternative Approach: The USDOT VAST Tool*

While the CDOT Method serves as a quantitative method to calculate for monetized risk and resilience measures ($/year), the U.S. The Department of Transportation's Vulnerability Assessment Scoring Tool (VAST) may be used as an alternative approach to calculate relative vulnerability scores on a macroscopic level. Such an approach is used when we need a rough estimate of an asset's vulnerability but lack the data necessary to compute for all road segments.

The VAST calculates vulnerability as a function of exposure, sensitivity, and adaptive capacity and provides a library of indicators for each of these qualities. Each indicator can be attributed to a score ranging from 1 to 4 based on various features of a relevant asset. For instance, a score of 1 assigned to an indicator signifies that an indicator suggests the asset's features minimize vulnerability, and a score of 4 assigned to an indicator suggests that the asset's features contribute heavily to vulnerability. For the case study of USVI Routes 30 and 32, we used specific indicators and assigned each indicator their respective scores.

**Step 1: Climate Stressor and Asset Type**

For the scope of our study, we are analyzing Routes 30 and 32 segments as transportation assets, both of which are roadway pavements with over 75% of their selected segments in a 100-year flood zone. Their significant exposure to the FEMA Coastal Flood Zone supports that they are prone to flood related hazards.

**Step 2: Exposure Analysis**

Exposure indicators for each segment are as follows:

1. Route 30
    - Proximity to Coastline, Score 4: Since much of the selected segment of Route 30 lies directly along the coastline, this indicator is assigned a score of 4.
    - Presence in FEMA Coastal Flood Zone, Score 4: The VAST provides the following metric for scoring the percentage of the asset located in the FEMA flood zone:

**Table 15**: VAST Score Metric for FEMA Coastal Flood Zone Presence

| | | | |
|---|---|---|---|
| 0% | 0% | = | 1 |
| 0% | 33% | = | 2 |
| 33% | 67% | = | 3 |
| 67% | 100% | = | 4 |

As over 67% of Segment 1 lies in the 100-year flood zone, this indicator is assigned a score a 4.

2. Route 32
    - Proximity to Coastline, Score 3: A part of the selected segment of Route 32 is near the coastline, but it is not positioned as close to the coastline as Route 30 is, so this indicator is assigned a score of 3.
    - Presence in FEMA Coastal Flood Zone, Score 4: This indicator is also given a score of 4, because as aforementioned with Route 30's Presence in FEMA Coastal Flood Zone, over 67% of its chosen length lies in the 100-year flood zone.

**Step 3: Sensitivity Analysis**
Sensitivity indicators for each segment are as follows:

1. Route 30
    - Past Experience with Storm Surge, Score 4: Since road segments that have been exposed to storm surge in the past are more likely to experience damage if exposed again, the VAST states that an asset with previous damage due to storm surge should receive a score of 4 for this indicator. Otherwise, the asset receives a score of 1. Since 2017 Hurricanes Irma and Maria devastated St. Thomas and caused extensive damage to roadways, this indicator is assigned a score of 4.
    - Past Experience with Tides/ SLR, Score 4: Since roads which have experienced flooding before are likely to experience it again, the VAST states that an asset with previous damage due to extreme high tide events should receive a score of 4 for this indicator. Otherwise, the asset receives a score of 1. Because Route 30 was affected by Hurricanes Irma and Maria, this indicator was assigned a score of 4.
2. Route 32
    - Past Experience with Storm Surge, Score 4: Similar to Route 30, Route 32 was hindered by the aforementioned hurricanes, so this indicator is scored at a 4.
    - Past Experience with Tides/SLR, Score 1: While Route 32 experienced storm surges, it did not have past experience with Tides/SLR due to its proximity to the coastline.

**Step 4: Adaptive Capability Analysis**
Adaptive capacity indicators for each segment are as follows:

1. Route 30
    - Route Replacement Cost, Score 3: The VAST provides the following metric for scoring the replacement cost of an asset:

**Table 16**: VAST Score Metric for Route Replacement Cost

| | | | |
|---|---|---|---|
| 0 | $1,000,000 | = | 1 |
| $1,000,000 | $10,000,000 | = | 2 |
| $10,000,000 | $100,000,000 | = | 3 |
| $100,000,000 | + | = | 4 |

Since the replacement cost of the relevant road section is $11,934,055, this indicator is assigned a score of 3.

- Detour Length, Score 1: The VAST provides the following metric (in km) for scoring the detour length if a particular asset is damaged:

**Table 17**: VAST Score Metric for Detour Length

| | | | |
|---|---|---|---|
| 0 | 10 | = | 1 |
| 10 | 30 | = | 2 |
| 30 | 50 | = | 3 |
| 50 | + | = | 4 |

Since the relevant road section has a detour length of 6.8 miles, this indicator is assigned a score of 1.

- Disruption Duration, Score 2: The VAST provides the following metric for scoring the disruption duration if an asset is damaged to the point of closure:

**Table 18**: VAST Score Metric for Disruption Duration

| | |
|---|---|
| Hours | 1 |
| Days | 2 |
| Weeks | 3 |
| Months | 4 |

Since the disruption duration for the relevant asset/threat combination is 3 days, this indicator is assigned a score of 2.

2. Route 32
    - Route Replacement Cost, Score 2: Since the replacement cost of the relevant segment is $2,599,919, this indicator is assigned a score of 3.
    - Detour Length, Score 2: Since the relevant road segment has a detour length of 9.3 miles, this indicator is assigned a score of 2.

- Disruption Duration, Score 2: Route 32 has the same relevant asset/threat combination as Route 30.

**Step 5: Vulnerability Scoring**
The Asset's total Exposure, Sensitivity, and Adaptive Capacity Scores are calculated as simple average scores of the respective indicators.

For Route 30,
Exposure Score = (4+4)/2 = 4
Sensitivity Score = (4+4)/2 = 4
Adaptive Capacity Score = (3+1+2)/3 = 2

For Route 32,
Exposure Score = (3+4)/2 = 3.5
Sensitivity Score = (4+1)/2 = 2.5
Adaptive Capacity Score = (2+2+2)/3 = 2

The final Vulnerability Score is then calculated as a simple average of the Exposure, Sensitivity, and Adaptive Capacity Scores.

Vulnerability Score for Route 30 = (4+4+2)/3 = 3.33
Vulnerability Score for Route 32 = (3.5+2.5+2)/3= 2

**Table 19**: Final USVI Segment 1 and 2 Vulnerability Calculations through the VAST Based Approach

| | **Route 30 (Veterans Drive)** | **Route 32/Turpentine Run Rd** |
|---|---|---|
| Exposure Indicators | Proximity to Coastline, Score 4 (all near coastal line)<br>Presence in FEMA Coastal Flood Zone, Score 4 (>75% in 100-year flood zone) | Proximity to Coastline, Score 3 (part near coastal line)<br>Presence in FEMA Coastal Flood Zone, Score 4 (>75% in 100-year flood zone) |
| Sensitivity Indicators | Past Experience with Storm Surge, Score 4<br>**Past Experience with Tides/SLR, Score 4 (yes, 4; no 1)**<br>**Elevation, Score 4 (1.58m)**<br>Flood protection (unknown) | Past Experience with Storm Surge, Score 4<br>**Past Experience with Tides/SLR, Score 1 (yes, 4; no 1)**<br>**Elevation, Score 3 (17.5m)**<br>Flood protection (unknown) |

| | | |
|---|---|---|
| | Soil (need more data)<br>**Pavement condition, Score 2 (3 good)** | Soil (need more data)<br>**Pavement condition 2, Score 3 (2 fair)** |
| <u>Adaptive Capacity Indicators</u> | Replacement Cost, Score 3 ($10M-$100M)<br>Detour Length, Score 1 (<10km)<br>Disruption Duration, Score 2 (days)<br>Location Criticality, Score 3 | Replacement Cost, Score 2 ($1M-$10M)<br>Detour Length, Score 2 (10km – 30km)<br>Disruption Duration, Score 2 (days)<br>Location Criticality, Score 1 |
| **Total Vulnerability Score** | **3.1** | **2.5** |

These vulnerability scores are not standalone, standardized metrics, but rather a scale that can be internally applied within an agency's system, to gauge and compare the relative vulnerabilities and risk levels of system assets. It is thus able to incorporate more qualitative factors as well as agency-specific parameters, at the expense of standardization between agencies through a shared or unified risk assessment scale.

### Network-Level Analysis

Network-level analysis lets us apply the risk values that we calculated from the above risk assessment methods to develop a more holistic understanding of similar transportation assets in that area. With this, we can make assumptions about how specific transportation assets would behave under specific treatments and methods. As discussed in section 3.2, the following pavement maintenance scenarios are assumed and compared though the network analysis through different combinations of treatment actions. These actions include the following categories: reconstruction, major rehabilitation, minor rehabilitation, and preservation. Upon calculation of the following specific treatments for each action, risk maps are developed for five alternative maintenance scenarios in the table below.

**Table 20**: Five Alternative Maintenance Scenarios and their PSI ratings

<table>
<tr><th>PSI</th><th>Type of Maintenance</th><th colspan="5">Scenario</th></tr>
<tr><td>0 & 0.5</td><td>Pavement Reconstruction</td><td>Scenario #1</td><td rowspan="2">Scenario #2</td><td rowspan="3">Scenario #3</td><td rowspan="4">Scenario #4</td><td rowspan="5">Scenario #5: PSI of 3 or less and above average usage</td></tr>
<tr><td>1 & 1.5</td><td>Major Pavement Rehabilitation</td><td></td></tr>
<tr><td>2 & 2.5</td><td>Minor Pavement Rehabilitation</td><td colspan="2"></td></tr>
<tr><td>3 & 3.5 & 4</td><td>Pavement Preservation</td><td colspan="3"></td></tr>
<tr><td>4.5 & 5</td><td>Do Nothing</td><td colspan="4"></td></tr>
</table>

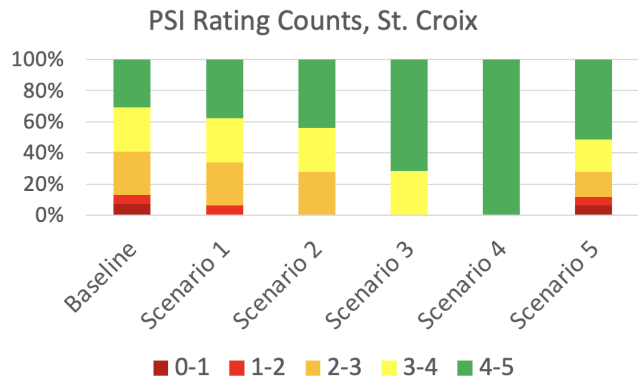



**Figure 36**: St. Croix pavement rating distribution compared for maintenance scenarios

All of these scenarios were compared by the following measures:

1. Investment (maintenance cost)
2. Miles-Weighted Average Network PSI Rating
3. Total Annual Owner Risk
4. Annual Owner Risk Reduction

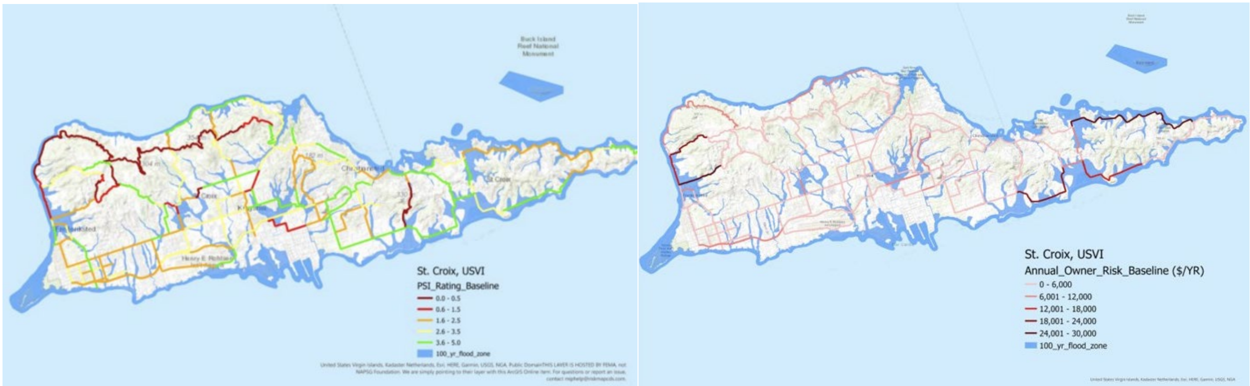
Note that we estimate the average weighted Network PSI level by multiplying the area of each pavement section by the PSI level for all sections and then divide the total by the total area, before and after the treatments are applied in the five defined scenarios. Total benefit and cost for each maintenance scenario relative to the baseline scenario will be listed in our economic analysis in section 3.5.

**Baseline**

The baseline is used as a status quo to compare to other intervention or investment scenarios. Baseline miles-weighted average PSI rating and total annual owner risk are presented for each island and across the USVI in Table 21, and Figure 37 shows pavement condition and annual owner risk maps of the pavement system across St. Croix as an illustrative example. For each alternative maintenance scenario, the difference in annual owner risk from the baseline risk- savings from mitigating risk in each scenario compared to the status quo- is calculated as part of risk assessment for the USVI and individual islands' networks. Average network PSI ratings and pavement condition maps show the impacts of maintenance scenarios compared to this baseline.

**Table 21**: USVI Pavement Baseline for Alternative Maintenance Scenarios

| | St. Croix | St. Thomas | St. John | USVI Total |
|---|---|---|---|---|
| Miles-Weighted Avg Network PSI Rating | 2.81 | 3.45 | 3.86 | 3.12 |
| Total Annual Owner Risk | $374,442 | $204,725 | $41,814 | $616,981 |




(a) (b)

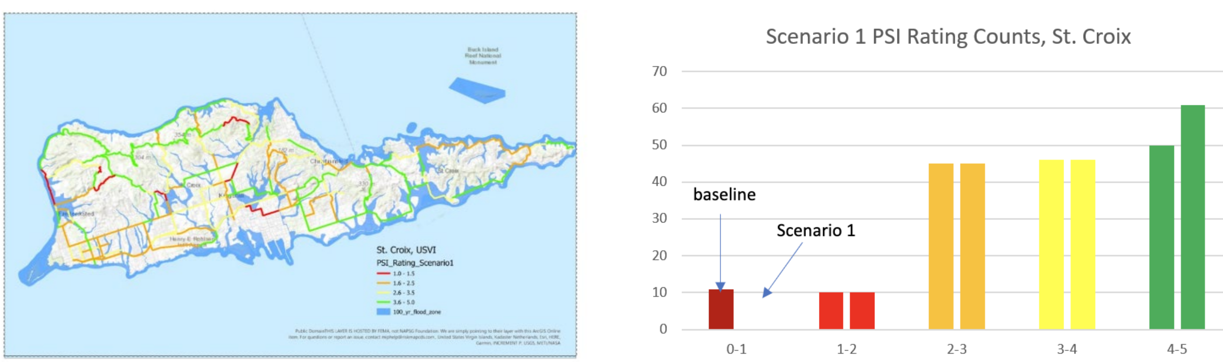
**Figure 37**: St. Croix pavement baseline scenario maps of (a) PSI rating distribution and (b) annual owner risk

**Scenario 1**

Scenario 1 states to perform only reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise the PSI to 5.

**Table 22**: USVI Pavement Alternative Scenario 1 Network Condition and Owner Risk

| | St. Croix | St. Thomas | St. John | USVI Total |
|---|---|---|---|---|
| Investment | $70,285,837 | $3,617,062 | $1,939,036 | $75,841,934 |
| Miles-Weighted Avg Network PSI Rating | 3.37 | 3.51 | 3.93 | 3.48 |
| Total Annual Owner Risk | $369,559 | $204,725 | $41,814 | $616,098 |
| Annual Owner Risk Reduction | $4,883 | $0 | $0 | $4,883 |




(a) (b)

**Figure 38**: St. Croix pavement Scenario 1 PSI rating (a) distribution map and (b) distribution chart compared to baseline

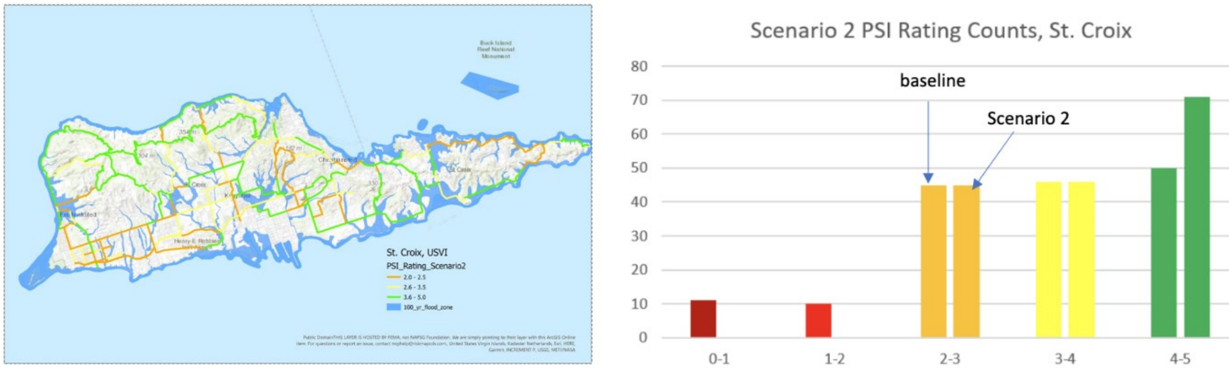

**Figure 39**: St. Croix pavement Scenario 1 annual owner risk map

**Scenario 2**

Scenario 2 states to perform reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise the PSI to 5 and conduct major rehabilitation for all pavements between PSI ratings 1-2 (1 and 1.5) to raise the PSI to 5.

**Table 23**: USVI Pavement Alternative Scenario 2 Network Condition and Owner Risk

| | St. Croix | St. Thomas | St. John | USVI Total |
|---|---|---|---|---|
| Investment | $82,218,711 | $5,479,655 | $1,939,036 | $89,637,402 |
| Miles-Weighted Avg Network PSI Rating | 3.57 | 3.54 | 3.93 | 3.61 |
| Total Annual Owner Risk | $364,485 | $204,290 | $41,814 | $610,588 |
| Annual Owner Risk Reduction | $9,957 | $436 | $0 | $10,393 |




(a) (b)

**Figure 40**: St. Croix pavement Scenario 2 PSI rating (a) distribution map and (b) distribution chart compared to baseline

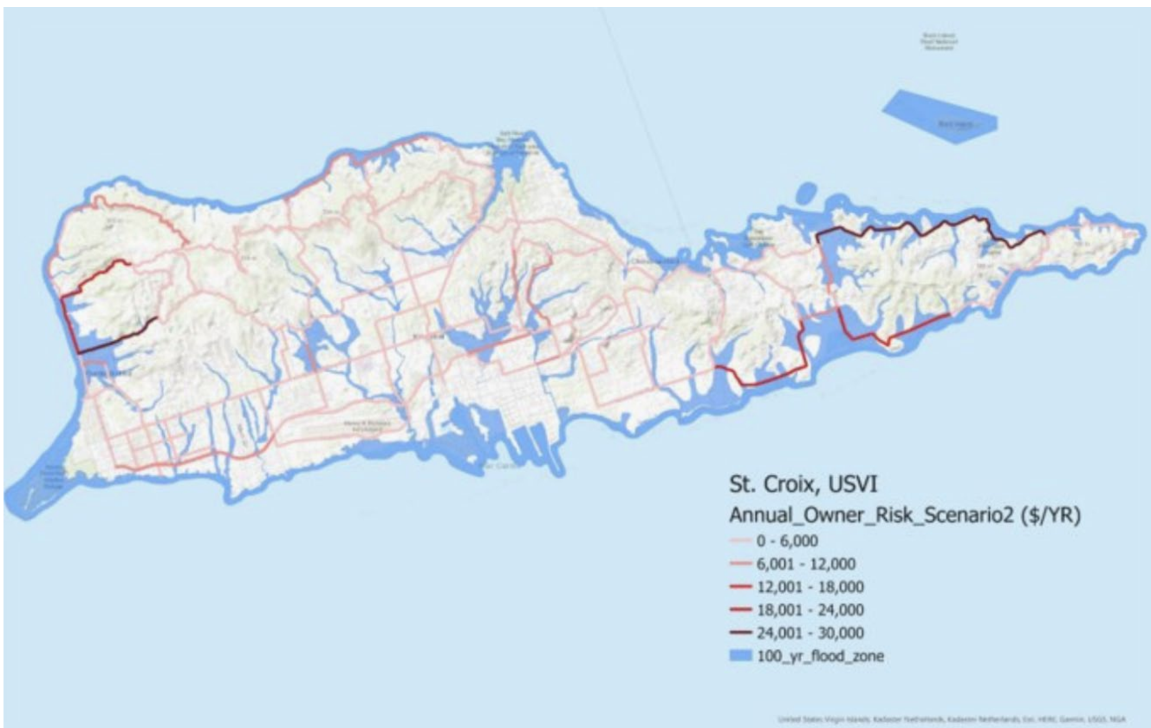



**Figure 41**: St. Croix pavement Scenario 2 annual owner risk map

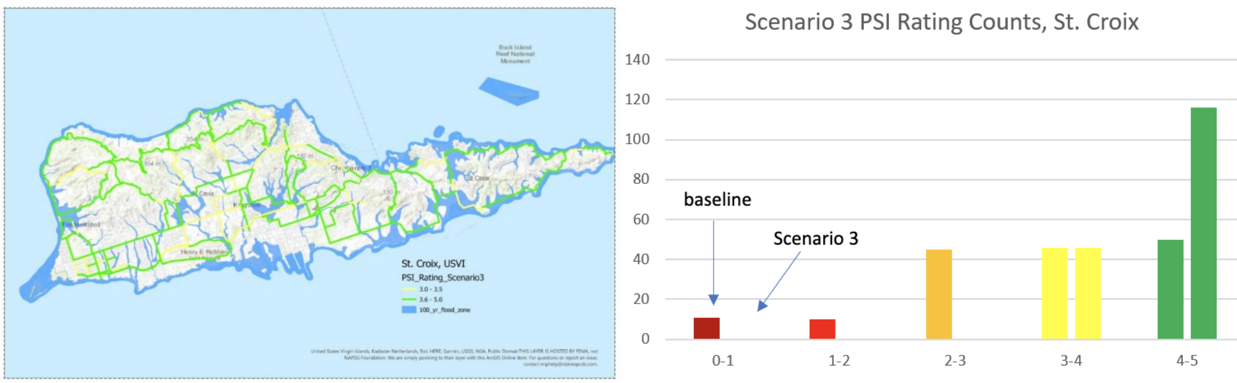
**Scenario 3**

Scenario 3 states to perform reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise the PSI to 5, major rehabilitation for all pavements between PSI ratings 1-2 (1 and 1.5) to raise the PSI to 5, and minor rehabilitation for all pavements between PSI Ratings 2-3 (2 and 2.5) to raise the PSI to 5.

**Table 24**: USVI Pavement Alternative Scenario 3 Network Condition and Owner Risk

| | St. Croix | St. Thomas | St. John | USVI Total |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Investment | $129,771,038 | $31,944,768 | $6,857,996 | $168,573,802 |
| Miles-Weighted Avg Network PSI Rating | 4.37 | 4.02 | 4.13 | 4.25 |
| Total Annual Owner Risk | $342,759 | $200,788 | $40,897 | $584,444 |
| Annual Owner Risk Reduction | $31,683 | $3,938 | $917 | $36,537 |




(a) (b)

**Figure 42**: St. Croix pavement Scenario 3 PSI rating (a) distribution map and (b) distribution chart compared to baseline


**Figure 43**: St. Croix pavement Scenario 3 annual owner risk map

**Scenario 4**

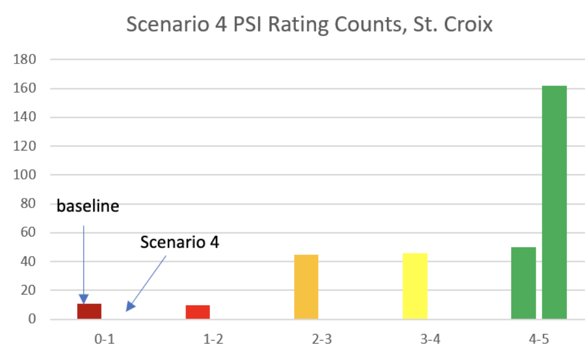
Scenario 4 states to perform reconstruction for all pavements under PSI rating 1 (0 and 0.5) to raise the PSI to 5, major rehabilitation for all pavements between PSI ratings 1-2

(1 and 1.5) to raise the PSI to 5, minor rehabilitation for all pavements between PSI Ratings 2-3 (2 and 2.5) to raise the PSI to 5, and preservation for all pavement between PSI rating 3-4.5 (3, 3.5 and 4) to raise PSI to 5.

**Table 25**: USVI Pavement Alternative Scenario 4 Network Condition and Owner Risk

| | St. Croix | St. Thomas | St. John | USVI Total |
|---|---|---|---|---|
| Investment | $158,256,200 | $61,559,342 | $17,158,965 | $236,974,507 |
| Miles-Weighted Avg Network PSI Rating | 4.99 | 4.93 | 4.94 | 4.96 |
| Total Annual Owner Risk | $324,136 | $188,295 | $37,686 | $550,116 |
| Annual Owner Risk Reduction | $50,306 | $16,431 | $4,128 | $70,865 |


(a)




(b)

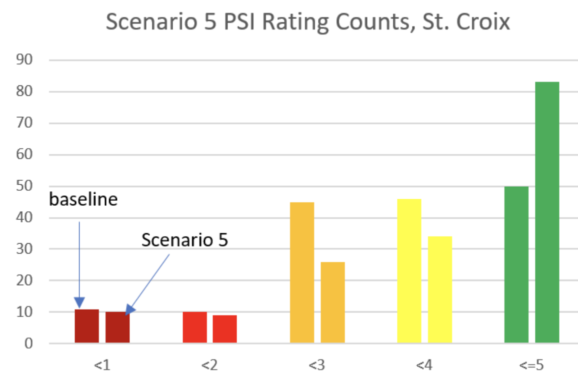
**Figure 44**: St. Croix pavement Scenario 4 PSI rating (a) distribution map and (b) distribution chart compared to baseline

**Figure 45**: St. Croix pavement Scenario 4 annual owner risk map

**Scenario 5**
Scenario 5 states to perform reconstruction for selected pavements under PSI rating 1 (0 and 0.5) to raise PSI to 5, major rehabilitation for selected pavement between PSI ratings 1-2 (1 and 1.5) to raise the PSI to 5, and minor rehabilitation for selected pavements between PSI ratings 2-3 (2 and 2.5) to raise the PSI to 5.

**Table 26**: USVI Pavement Alternative Scenario 5 Network Condition and Owner Risk

| | St. Croix | St. Thomas | St. John | USVI Total |
|---|---|---|---|---|
| Investment | $32,112,363 | $21,509,553 | $3,125,288 | $56,757,145 |
| Miles-Weighted Avg Network PSI Rating | 3.35 | 3.99 | 4.14 | 3.62 |
| Total Annual Owner Risk | $363,340 | $196,948 | $41,814 | $602,102 |
| Annual Owner Risk Reduction | $11,102 | $7,777 | $0 | $18,879 |


(a) (b)

**Figure 46**: St. Croix pavement Scenario 5 PSI rating (a) distribution map and (b) distribution chart compared to baseline


**Figure 47**: St. Croix pavement Scenario 5 annual owner risk map

From these alternative pavement scenario risk assessments, we can now apply the annual network risk reductions we found and integrate them into other analyses, incorporating the impacts of this normal condition maintenance- improved pavement condition- into risk mitigation and management to build resilience in extreme condition. This would be at the discretion of the transportation agency conducting the network-level study, which could be considered in a greater benefit-cost or economic impact analysis for risk-based asset management. Section 3.5 goes further into detail with savings from normal condition maintenance and their economic impact, as well as consideration of investment levels for the above alternative scenarios.

## 3.5 Economic Impact Analysis and Benefit Cost Analysis (BCA)

The economic analysis evaluates the costs and savings associated with intervention scenarios to determine their efficiencies, and we conduct an EIA here for the five pavement or roadway intervention scenarios presented in 3.2.2 and 3.4.2. The baseline estimates are the current expenses to maintain the roads as-is and are used as a comparison to the intervention scenarios to demonstrate how much money has been saved through improved maintenance approaches, by both users of the system and agencies managing it. In order to understand how routine infrastructure maintenance can improve the Territory's overall resilience and economic growth, we must first estimate the baseline costs associated with subpar roadway maintenance.

Currently, the subpar road conditions in USVI greatly affect citizens and tourists who are utilizing the infrastructure. To estimate the citizen costs, we must evaluate individual road segments. The categories measured are the wear and tear on vehicles, loss of time in traffic, and the negative effects of the idle time, pollution costs, and breeches of safety. Figure 48 exhibits the breakdown of these costs associated with poor transportation infrastructure.

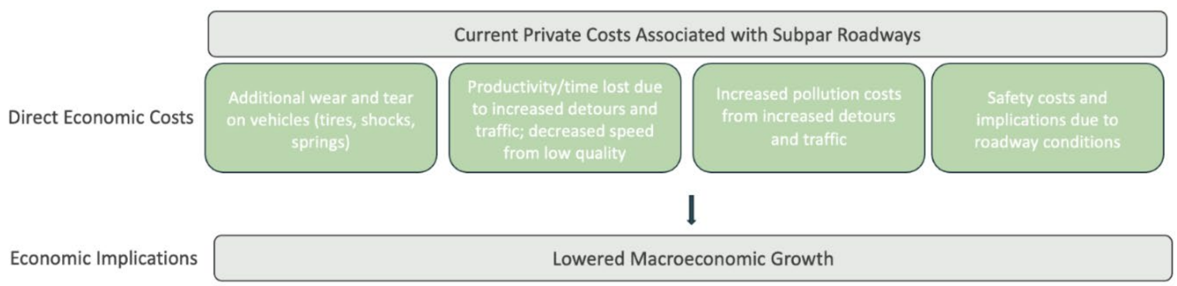



**Figure 48**: Direct sources of "the cost of doing nothing"

### Roadway Baseline Costs

To determine what current economic costs are, we must first gauge the traffic on these roads, as well as the current state of repair needed. To evaluate the basis for road usage, a set of data is analyzed that includes the annual average daily traffic split into trucks and passenger vehicles, peak hour volume, detour routes, and redundancy. Next, the quality of each road on each island will be assessed using PSI, which is the present serviceability index measuring roadway condition. It is based on the original AASHO Road Test PSR and ranges from 0, which is very poor, to 5, which is very good. The traffic/usage and PSI are combined to get an exhaustive view of the state of the roadways and infrastructure on each island.

The direct economic consequences of not conducting roadway maintenance, as mentioned above, include wear and tear on vehicles--such as tires, and springs, detour costs (which include user costs, value of time, emissions, and gas), and crash costs. Table 27 demonstrates the broken-down baseline costs for each of the USVI Islands, as well as the total losses for each component. The additional expenses that we have not quantified are the detour costs which include loss of time and productivity in traffic and ripple effects of idle time, pollution costs based on increased idling time, and safety implications of poor infrastructure.

**Table 27**: Baseline Estimates of Total Costs Associated with Subpar USVI Roadways

| | St. Croix | St. Thomas | St. John | Total |
|---|---|---|---|---|
| **Wear and Tear** | $9,450,211 | $3,598,650 | $191,534 | $13,240,394 |
| **Detour Costs (probabilistic)** | | | | |
| User Costs | $9,369 | $14,220 | $1,041 | $24,630 |
| Value of Time | $16,837 | $18,995 | $1,485 | $37,317 |
| Emissions | 3.64 | 4.01 | 0.31 | 7.96 |
| Gas | $1,482 | $1,632 | $128 | $3,241 |
| **Crash Costs** | $45,460,814 | $35,501,903 | $969,287 | $81,932,004 |
| **Total Costs** | $54,938,713 | $39,135,400 | $1,163,475 | **$95,237,588** |

This estimation allows us to assess the economic impact of properly managed infrastructure based on crash savings and wear and tear savings from this baseline of insufficient maintenance. Crash savings consist of how often accidents occur and take into consideration the cost for fatalities, injuries, and property damage. Poorly maintained roads increase the frequency and severity of accidents. Through correlation analysis of accident severity and frequency with subpar road conditions by Zaoloshnja and Miller, we can estimate and calculate the added costs of accidents due to subpar roadway conditions in the USVI, using data from the Virgin Islands Offices of Highway Safety 2019 Annual Report.

## Roadway Intervention Scenario Costs and Savings

Crash savings are calculated utilizing the percent of subpar roadways, multiplied by the percent of costs in which roadway conditions were a contributing factor to increased costs, multiplied by the total cost for road damage such death, injury, and vehicle damage.

$$\begin{aligned}&\mathit{Crash\ Costs\ associated\ with\ subpar\ roadways}\\&= (\%\ \mathit{of\ subpar\ roadway}) * (\%\ \mathit{of\ costs\ in\ which\ roadway\ conditions\ were\ a\ contributing\ factor\ to\ increased\ costs})\\&* (\mathit{total\ annual\ costs\ associated\ with\ death, injuries, and\ vehicle\ damage\ per\ island})\end{aligned}$$

**Equation 5**: Crash costs due to subpar roadway condition calculation

Wear and tear savings are composed of the costs associated with damage done on the pavement by vehicles. Previous literature finds that any road segment with an index of less than 3.5 will result in additional per-mile maintenance costs in terms of increased maintenance, repairs, tires, and depreciation costs. These costs will be estimated per island based on road usage and PSR rating for both personal vehicles and trucks.

$$Added\ wear\ and\ tear\ due\ to\ subpar\ roadways = PSI\ Adjustment\ Factor * [(AnnualVMT_{cars} * \$0.30\ per\ mile) + (AnnualVMT_{trucks} * \$0.33\ per\ mile)]$$

$$\begin{aligned} where\ PSI\ Adjustment\ Factor &= 0.25\ if\ PSI =< 2 \\ &= 0.15\ if\ PSI = 2.5 \\ &= 0.05\ if\ PSI = 3 \end{aligned}$$

**Equation 6**: Wear and tear costs due to subpar roadway condition calculation

Wear and tear savings are calculated from multiplying the PSI Adjustment Factor to the total of the annual vehicle miles traveled for cars times $0.30 per mile plus the annual vehicle miles traveled for trucks times $0.31 per mile. The PSI Adjustment Factor is determined by the PSI level. If the PSI is less than or equal to 2, the adjustment factor is 0.25. If the PSI equals 2.5, the adjustment factor is 0.15. If the PSI is 3, the adjustment factor is 0.05.

Using these calculation methods, we present the following cost savings totals for pavement intervention Scenarios 1 through 5 as defined in 3.2.2 (see Table 6 or descriptions below), compared to the baseline scenario and its costs.

**Scenario 1:**
Scenario 1 consists of pavement reconstruction for roads with a PSI of 0 – 0.5. Table 28 shows the breakdown for crash savings and Table 29 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

**Table 28**: Roadway Intervention Scenario 1 Crash Savings Breakdown

| | St. Croix | St. Thomas | St. John | USVI Total | Savings |
|---|---|---|---|---|---|
| Total Comprehensive Crash Costs | $41,691,414 | $34,961,886 | $953,914 | **$77,607,215** | **$4,324,790** |
| Fatalities | $16,776,454 | $11,025,425 | $0 | $27,801,879 | $1,687,088 |
| Injuries | $23,765,138 | $22,389,089 | $898,305 | $47,052,532 | $2,508,947 |
| Private Property | $1,149,822 | $1,547,372 | $56,506 | $2,753,700 | $127,858 |

**Table 29**: Roadway Intervention Scenario 1 Wear and Tear Savings Breakdown

| | St. Croix | | St. Thomas | | | St. John | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| PSI | Percent of Daily Vehicle Miles Traveled by PSI | Additional Wear and Tear from Poorly Maintained Roads | PSI | Percent of Daily Vehicle Miles Traveled by PSI | Additional Wear and Tear from Poorly Maintained Roads | USVI Total | Percent of Daily Vehicle Miles Traveled by PSI | Additional Wear and Tear from Poorly Maintained Roads | Additional Wear and Tear from Poorly Maintained Roads |
| 0-2 | 16% | $4,102,043 | 0-2 | 12% | $1,927,966 | 0-2 | 3% | $51,777 | $6,081,785 |
| 2.5 | 20% | $3,117,909 | 2.5 | 7% | $716,279 | 2.5 | 3% | $25,784 | $3,859,972 |
| 3 | 18% | $954,635 | 3 | 26% | $842,006 | 3 | 36% | $110,919 | $1,907,560 |
| 3.5-5 | 46% | $0 | 3.5-5 | 55% | $0 | 3.5-5 | 58% | $0 | $0 |
| Total | | $8,174,587 | Total | | $3,486,250 | Total | | $188,480 | $11,849,317 |
| **Difference from Baseline:** | | **$1,275,624** | **Difference from Baseline:** | | **$112,399** | **Difference from Baseline:** | | **$3,054** | **$1,391,077** |

For Scenario 1, the total savings from crashes are $4,324,790 and wear and tear are $1,391,077. This makes the overall savings $5,715,867. Because $75,841,938 is the amount invested when scenario 1 occurs, the ROI (return on investment) is 0.08 in total, with the ROI for crash and wear and tear being 0.02 and 0.06 respectively.

**Scenario 2:**
Scenario 2 consists of major pavement rehabilitation for roads with a PSI of 1.0 – 1.5, in addition to scenario 1 (reconstruction of roads with a PSI 0 – 0.5). Table 30 shows the breakdown for crash savings and Table 31 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

**Table 30**: Roadway Intervention Scenario 2 Crash Savings Breakdown

| | St. Croix | St. Thomas | St. John | USVI Total | Savings |
|---|---|---|---|---|---|
| Total Comprehensive Crash Costs | $40,546,690 | $34,187,470 | $953,914 | **$75,688,074** | **$6,243,930** |
| Fatalities | $16,315,822 | $10,781,208 | $0 | $27,097,030 | $2,391,937 |
| Injuries | $23,112,617 | $21,893,164 | $898,305 | $45,904,086 | $3,657,393 |
| Private Property | $1,118,251 | $1,513,097 | $55,609 | $2,686,958 | $194,600 |

**Table 31**: Roadway Intervention Scenario 2 Wear and Tear Savings Breakdown

| St. Croix | | | St. Thomas | | | St. John | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| PSI | Percent of Daily Vehicle Miles Traveled by PSI | Additional Wear and Tear from Poorly Maintained Roads | PSI | Percent of Daily Vehicle Miles Traveled by PSI | Additional Wear and Tear from Poorly Maintained Roads | USVI Total | Percent of Daily Vehicle Miles Traveled by PSI | Additional Wear and Tear from Poorly Maintained Roads | Additional Wear and Tear from Poorly Maintained Roads |
| 0-2 | 14% | $3,714,146 | 0-2 | 11% | $1,765,842 | 0-2 | 3% | $51,777 | $5,531,764 |
| 2.5 | 20% | $3,117,909 | 2.5 | 7% | $716,279 | 2.5 | 3% | $25,784 | $3,859,972 |
| 3 | 18% | $954,635 | 3 | 26% | $842,006 | 3 | 36% | $110,919 | $1,907,560 |
| 3.5-5 | 47% | $0 | 3.5-5 | 56% | $0 | 3.5-5 | 58% | $0 | $0 |
| Total | 100% | $7,786,690 | Total | 100% | $3,324,126 | Total | 100% | $188,480 | $11,299,296 |
| **Difference from Baseline:** | | **$1,663,521** | **Difference from Baseline:** | | **$274,523** | **Difference from Baseline:** | | **$3,054** | **$1,941,098** |

For Scenario 2, the total savings from crashes are $46,851,323 and wear and tear are $11,332,834. This makes the overall savings $58,184,157. Because $168,573,804 is the amount invested for scenario 2, the ROI (return on investment) is 0.35 in total, with the ROI for crash and wear and tear being 0.28 and 0.07 respectively.

**Scenario 3:**
Scenario 3 consists of minor pavement rehabilitation for roads with a PSI of 2 – 2.5, in addition to scenario 2. Table 32 shows the breakdown for crash savings and Table 33 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

**Table 32**: Roadway Intervention Scenario 3 Crash Savings Breakdown

| | St. Croix | St. Thomas | St. John | USVI Total | Savings |
|---|---|---|---|---|---|
| Total Comprehensive Crash Costs | $14,142,229 | $20,124,181 | $814,272 | **$35,080,682** | **$46,851,323** |
| Fatalities | $5,690,775 | $6,346,272 | $0 | $12,037,047 | $17,451,920 |

| | | | | | |
|---|---|---|---|---|---|
| Injuries | $8,061,421 | $12,887,236 | $766,803 | $21,715,460 | $27,846,020 |
| Private Property | $390,033 | $890,673 | $47,469 | $1,328,175 | $1,553,383 |

**Table 33**: Roadway Intervention Scenario 3 Wear and Tear Savings Breakdown

| PSI | St. Croix: Percent of Daily Vehicle Miles Traveled by PSI | St. Croix: Additional Wear and Tear from Poorly Maintained Roads | St. Thomas: Percent of Daily Vehicle Miles Traveled by PSI | St. Thomas: Additional Wear and Tear from Poorly Maintained Roads | St. John (USVI Total): Percent of Daily Vehicle Miles Traveled by PSI | St. John (USVI Total): Additional Wear and Tear from Poorly Maintained Roads | Total: Additional Wear and Tear from Poorly Maintained Roads |
|---|---|---|---|---|---|---|---|
| 0-2 | 0% | $0 | 0% | $0 | 0% | $0 | $0 |
| 2.5 | 0% | $0 | 0% | $0 | 0% | $0 | $0 |
| 3 | 18% | $954,635 | 26% | $842,006 | 36% | $110,919 | $1,907,560 |
| 3.5-5 | 82% | $0 | 74% | $0 | 64% | $0 | $0 |
| Total | 100% | $954,635 | 100% | $842,006 | 100% | $110,919 | $1,907,560 |
| **Difference from Baseline:** | | **$8,495,576** | | **$2,756,644** | | **$80,614** | **$11,332,834** |

For Scenario 3, the total savings from crashes are $ 46,851,323 and wear and tear are $11,332,834. This makes the overall savings $ 58,184,157. Because $168,573,804 is the amount invested for scenario 3, the ROI (return on investment) is 0.35 in total, with the ROI for crash and wear and tear being 0.28 and 0.07 respectively.

**Scenario 4:**
Scenario 4 consists of pavement preservation for roads with a PSI of 3 – 4, in addition to scenario 3. Table 34 shows the breakdown for crash savings and Table 35 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

**Table 34**: Roadway Intervention Scenario 4 Crash Savings Breakdown*

| | St. Croix | St. Thomas | St. John | USVI Total | Savings |
|---|---|---|---|---|---|
| Total Comprehensive Crash Costs | $0 | $0 | $0 | $0 | **$81,932,004** |
| Fatalities | $0 | $0 | $0 | $0 | $29,488,967 |
| Injuries | $0 | $0 | $0 | $0 | $49,561,479 |
| Private Property | $0 | $0 | $0 | $0 | $2,881,558 |

**Table 35**: Roadway Intervention Scenario 4 Wear and Tear Savings Breakdown*

| PSI | St. Croix: Percent of Daily Vehicle Miles Traveled by PSI | St. Croix: Additional Wear and Tear from Poorly Maintained Roads | St. Thomas: Percent of Daily Vehicle Miles Traveled by PSI | St. Thomas: Additional Wear and Tear from Poorly Maintained Roads | St. John (USVI Total): Percent of Daily Vehicle Miles Traveled by PSI | St. John (USVI Total): Additional Wear and Tear from Poorly Maintained Roads | Total: Additional Wear and Tear from Poorly Maintained Roads |
|---|---|---|---|---|---|---|---|
| 0-2 | 0% | $0 | 0% | $0 | 0% | $0 | $0 |
| 2.5 | 0% | $0 | 0% | $0 | 0% | $0 | $0 |
| 3 | 0% | $0 | 0% | $0 | 0% | $0 | $0 |
| 3.5-5 | 100% | $0 | 100% | $0 | 100% | $0 | $0 |
| Total | 100% | $0 | 100% | $0 | 100% | $0 | $0 |
| **Difference from Baseline:** | | **$9,450,211** | | **$3,598,650** | | **$191,534** | **$13,240,394** |

For Scenario 4, the total savings from crashes are $81,932,004 and wear and tear are $13,240,394. This makes the overall savings $95,172,399. Because $236,974,508 is the amount invested for scenario 4, the ROI (return on investment) is 0.40 in total, with the ROI for crash and wear and tear being 0.35 and 0.06 respectively.

**Note: The crash savings and wear and tear savings are $0 given that this scenario is the best case for crashes and wear and tear (all pavement is brought to PSI level of 5), so we can assume that the agency has already done everything it can to improve the pavement to the best condition possible. Therefore, these costs cannot be reduced any further through maintenance, and are effectively zero.*

**Scenario 5:**
Scenario 5 consists of targeted pavement prioritization for roads with a PSI of 3 or less and above average usage. Table 36 shows the breakdown for crash savings and Table 37 shows the breakdown for wear and tear savings for St. Croix, St. Thomas, and St. John.

**Table 36**: Roadway Intervention Scenario 5 Crash Savings Breakdown

| | St. Croix | St. Thomas | St. John | USVI Total | Savings |
|---|---|---|---|---|---|
| Total Comprehensive Crash Costs | $14,311,079 | $11,511,617 | $378,436 | $26,201,132 | **$55,730,872** |
| Fatalities | $5,758,719 | $3,630,252 | $0 | $9,388,972 | $20,099,995 |
| Injuries | $8,157,669 | $7,371,874 | $356,375 | $15,885,918 | $33,675,561 |
| Private Property | $394,690 | $509,491 | $22,061 | $926,242 | $1,955,316 |

**Table 37**: Roadway Intervention Scenario 5 Wear and Tear Savings Breakdown

| St. Croix | | | St. Thomas | | | St. John | | | Total |
|---|---|---|---|---|---|---|---|---|---|
| PSI | Percent of Daily Vehicle Miles Traveled by PSI | Additional Wear and Tear from Poorly Maintained Roads | PSI | Percent of Daily Vehicle Miles Traveled by PSI | Additional Wear and Tear from Poorly Maintained Roads | USVI Total | Percent of Daily Vehicle Miles Traveled by PSI | Additional Wear and Tear from Poorly Maintained Roads | Additional Wear and Tear from Poorly Maintained Roads |
| 0-2 | 7% | $1,936,675 | 0-2 | 4% | $675,142 | 0-2 | 4% | $54,830 | $2,666,647 |
| 2.5 | 7% | $1,151,236 | 2.5 | 3% | $339,345 | 2.5 | 3% | $25,784 | $1,516,364 |
| 3 | 4% | $193,455 | 3 | 7% | $254,209 | 3 | 10% | $31,759 | $479,423 |
| 3.5-5 | 81% | $0 | 3.5-5 | 85% | $0 | 3.5-5 | 83% | $0 | $0 |
| Total | 100% | $3,281,365 | Total | 100% | $1,268,696 | Total | 100% | $112,374 | $4,662,434 |
| **Difference from Baseline:** | | **$6,168,846** | **Difference from Baseline:** | | **$2,329,954** | **Difference from Baseline:** | | **$79,160** | **$8,577,960** |

For Scenario 5, the total savings from crashes are $ 55,730,872 and wear and tear are $8,577,960. This makes the overall savings $ 64,308,832. Because $56,408,684 is the amount invested for scenario 5, the ROI (return on investment) is 1.41 in total, with the ROI for crash and wear and tear being 0.99 and 0.15 respectively.

## Comparison of Intervention Scenarios and EIA Conclusion

The return on investment (ROI) is a simple metric to evaluate how cost-effective or efficient an investment is. For each of the above roadway intervention scenarios, the ROI was calculated by dividing the total savings by the investments or intervention costs. For Scenario 1, the ROI was 0.08, which is extremely low because these roads are in the worst condition and need to be heavily invested in. The ROI for Scenario 2 is 0.09, which is only marginally higher than Scenario 1 and generally low because the road conditions are still very poor. Next, the ROI for Scenario 3 is 0.35, which is significantly higher than Scenarios 2 and 1 because far more roads are in fair condition (see Figure 11), so not much money needs to be invested for lower-intensity treatments on much more roadway, producing significantly more savings from crashes and wear and tear per mile. For Scenario 4, the ROI is 0.40 since the roads are in adequate condition, resulting in the use of less-costly preservation treatments on top of previous investments to minimize any costs due to roadway condition. Finally, the ROI for Scenario 5 is 1.14, which is much greater than the ROIs for all previous scenarios and even predicts a net economic gain from crash and wear and tear savings alone. Scenario 5 has the highest return on investment because it optimizes which are the most necessary roads to apply treatments to, instead of applying it to all the roads regardless of actual use or savings from less frequent accidents. By choosing which roads actually or direly need reconstruction, Scenario 5 is the most efficient in terms of economic impact analysis. While more data is needed and may affect relative economic impacts of each maintenance or intervention scenario, the data utilized paints a clear comparative look that favors prioritization of critical assets over more costly “fix worst first” or even fix-everything approaches.

# 4 Conclusion

## 4.1 Challenges for Risk-Integrated TIAM Program Implementation

As we demonstrated with coastal flooding risk in our U.S. Virgin Islands case study, existing risk/resilience analysis processes can be quantitatively integrated with existing asset management methodologies to produce useful, more comprehensive information for agencies. The outputs of our applied framework can then support risk-conscious decisions in day-to-day operational planning and capital project investment. Through the analyses we performed, however, we identified several challenges for executing our framework in the USVI and in general.

### Agency Resources to Implement Risk-Based TIAM Framework and Investment Strategies

Asset management as a common practice in transportation agencies arose out of increasingly limited agency budgets and personnel, as well as a shift in focus from network expansion to (more effective and accountable) network maintenance (OAM, 1999, pp. 10-12), and the USVI case is a particularly severe example of both issues. Our study determined that an extremely strained fiscal situation, largely dependent on funding from the Federal Transit Administration, FHWA, and special federal grants, has restricted major investments and interventions while limiting workforce numbers and equipment at the disposal of the USVI Department of Public Works (DPW), affecting both capital and operational projects carried out by the USVI’s DOT equivalent (Government, n.d.). Without sufficient funds, staff, and equipment to fully sustain and operate the transportation system in normal conditions, the USVI faces significant obstacles to executing major infrastructure projects, post-natural hazard recoveries, and risk mitigation or resiliency measures. We found that as a result, many assets (including roadway pavement, bridges, and culverts) remain in fair or worse condition, and recovery from damaging events is often delayed or limited. Interventions are often conducted in a “fix worst first” approach, with stretched resources sapped by much greater life cycle costs due to intensive reconstruction treatments on the most deteriorated assets. Thus, a primary challenge in improving the resilience and the general state of the USVI’s infrastructure is the securing of funding and resources to carry out a more comprehensive plan, so that costly reconstruction is not the USVI’s main intervention method. In other words, starting a more cost-effective or optimized TIAM program to produce cost savings in the long-term will depend on initial resources, in order to move beyond the “fix worst first” approach.

With specific regard to the USVI, implementing our risk-integrated framework and general asset management practices is more difficult because material and treatment costs are significantly higher than in the mainland U.S. Conducting any treatments beyond those absolutely necessary (reconstructions of the worst condition roads for reasonable safety) is thus very costly, which the USVI may not be able to pursue without additional resources. This limits what scenarios or strategies are financially viable in risk mitigation initiatives or even an asset management program in general, given current funding levels.

### Increasing Likelihood and Potential Consequences of Natural Hazards

Adding to the difficulty of infrastructure maintenance in normal conditions, the USVI has historically faced significant natural hazard events, and is expected to face more frequent and severe hazards in future- namely, tropical storms or hurricanes and coastal flood events. In 2017, the USVI was impacted by two Category 5 hurricanes in one season (Hurricanes Irma and Maria), and experienced extreme winds, precipitation, and flooding. Unfortunately, climate change is expected to lead to greater likelihood and strength of tropical cyclones, meaning increased risk for the USVI and other hurricane-prone regions. Some effects include overwhelmed drainage systems, increased debris and building damage, storm surge impacts on coastal infrastructure and communities, roadway deterioration, and flooding and erosion in low-lying areas and shores. Coastal areas will be further affected by sea level rise, contributing to flooding and erosion; coastal flood zones will expand. Finally, altered climate and precipitation patterns are expected to increase the severity and variability of rainfall events, which can cause surface flooding and also overwhelm drainage systems. With these more likely and more severe natural hazards in mind, the USVI has much work ahead to reduce the vulnerability and risk of its transportation system and the communities that rely on them.

An important additional factor to consider again is two-way impacts: subpar maintenance will contribute to worse damage and costlier recovery, while hazard damage and post-event vulnerability will contribute to faster deterioration and reduced resilience. A prime example of this bi-directional impact was observed following the USVI’s immediate recovery efforts after Hurricanes Irma and Maria. Intense rainfall caused extreme saturation of many roads’ base layers and subgrade, weakening their load-bearing capacities and reducing their resilient modulus or stiffness. With improper drainage and capillary action saturating drier areas of the pavement structure, moisture was able to severely weaken many roads' entire pavement structures, causing lasting effects on long-term strength and deterioration. This was worsened by heavy truck traffic in the cleanup and recovery after the hurricanes passed, with truck weights exceeding the lower post-event capacity that pavement structures could support. Pavement ultimately experienced failure, with many roads cracking at the surface and within the base layers. Exposed pavement following such damage only contributed to faster deterioration, with the shifted asphalt and cracks allowing further permeation and saturation in future rainfall events, causing further damage and worsened post-event road conditions. These two-way impacts between normal and extreme conditions must be accounted for when mitigating risk and predicting asset deterioration in the USVI and beyond, especially with more frequent events and recoveries expected in the future.

### Need for Comprehensive Data for Accurate Risk-Integrated TIAM Methodology and Analysis

The above two-way impact case from the USVI's pavement highlights another, broader issue facing the implementation of an effective risk-integrated TIAM program: collecting and incorporating enough data on assets and management practices, particularly the impacts of natural hazards. In executing our framework (and TIAM in general), one key requirement is collecting and managing sufficient relevant data, and here it is even more important so that probabilistic risk event impacts and normal condition deterioration on each other are modeled as accurately as possible. As we outlined and demonstrated via the USVI case, we can quantify and incorporate risk values into LCCA and EIA to better study and compare investment scenarios or strategies, but there is a significant number of factors and variables that play a role in both normal condition and extreme condition that need to be considered. Being unable to (quantitatively) account for enough factors- such as the reduced stiffness and strength of saturated pavement layers based on severe rain events- means that risk-integrated deterioration modeling and results of LCCA, BCA, and EIA could be inaccurate. In fact, as noted in 3.3.2, we did not conduct a long-term LCCA or LCP modeling for pavement, instead only completing normal condition TIAM assessment of deterioration and LCCA/network LCP for bridge asset scenarios in 3.4. This was due to a substantial lack of data, including information on soil and flood protection for roadways. The data that were available were sometimes outdated, such as a roadway traffic collection report from 2013, which similarly adds to possible inaccuracy. In our risk analysis, we had to make assumptions based on the 2020 CDOT Procedure and similar values from Puerto Rico, another U.S. island territory, for factors such as agency risk cost data and user data such as truck speed, vehicle occupancy, and running costs (in time and value). While other agencies in the U.S. may have more data that are also up to date, not all of this relevant data will necessarily be available or even feasible to collect in a regular, timely manner, so managers must be able to collect, maintain, and analyze what is possible to maintain accurate and reliable long-term predictions and planning. This includes information more traditional with TIAM, such as pavement or bridge deck condition, as well as data on natural hazards (likelihood, vulnerability, and consequences) and maintenance or management practices like treatment costs and intervention impacts.

## 4.2 Recommendations and Lessons for Risk-Based TIAM in the USVI and the Broader US

The same financial challenges in implementing risk mitigation, resilience planning, and general infrastructure projects and maintenance that the USVI faces can be better addressed with a coordinated TIAM program. While many of the intervention strategies presented may be fiscally infeasible at present, such an analytical approach may provide guidance on the optimal strategy to improve safety and produce cost savings and economic benefit for users and the community, reducing life cycle costs and future interventions compared to a “fix-the-worst” approach that is unsafe and more costly (for the agency, users, and community) in the long-term. Further funding could be acquired from dedicated federal resilience planning funds, awards for specific projects, or public-private partnerships, and allocated and raised for a sustainable Territorial transportation resilience fund.

Constrained budgets, insufficient maintenance, and increasing natural hazard impacts are not limited to the USVI. Once a risk-integrated TIAM program is initiated with better data collection, hazard identification and modeling, and analysis methodologies established, risk-integrated deterioration modeling, LCCA/LCP, EIA, and BCA can all be conducted to produce management and investment strategies optimized for strained agencies elsewhere by comparison of long-term treatment scenarios and impact on asset condition and cost(-benefit), as we performed. The process can support quantitative resilience planning through better risk prediction and mitigation strategies, particularly hardening and repair of assets identified for prioritization. Through BCA and criticality analysis, DOTs and agencies can prioritize investment to avoid suboptimal infrastructure conditions in critical assets that transportation systems depend on, maximizing beneficial social and economic impacts. Focusing their limited spending and resources on these key corridors with higher volumes of traffic or access to critical locations (e.g., hospitals or airports) will help build the resilience of systems and the communities that depend on them, especially in event aftermath and recovery.

We demonstrated this capability through our modeling and comparison of the five USVI scenarios for pavement management strategies in 3.5.2, with BCA predicting a full return on investment for a representative scenario when combining risk savings and economic impact for overall savings in the case study. Despite an investment level lower than the “fix-the-worst” approach as modeled by Scenario 1, Scenario 5’s targeted interventions on the most critical subpar roadway segments produced over 11 times as much overall savings as Scenario 1, while achieving a full ROI of 1.14 across the Territory. Not only was this the highest ROI estimate obtained out of the five scenarios, but it was also produced from the lowest level of investment (roughly $56.4 million) out of the five strategies, including the current “fix worst first” approach that solely involves the absolutely necessary end-of-life reconstruction of pavement, as modeled by Scenario 1 (~$75.8 million). Furthermore, the savings estimated to produce this full ROI were limited to cost savings from reduced vehicular wear and tear, detour costs, and accidents, thus omitting other economic impacts avoided (and further overall savings for users and the economy) such as losses in productivity, idling time and pollution, and ripple effects in local safety and economies. The EIA and BCA performed for USVI pavement interventions thus demonstrates how just from certain or limited quantifiable values and risk analysis, an analytical procedure for identifying a more optimal management strategy can still be achieved for cost-effectiveness and risk mitigation.

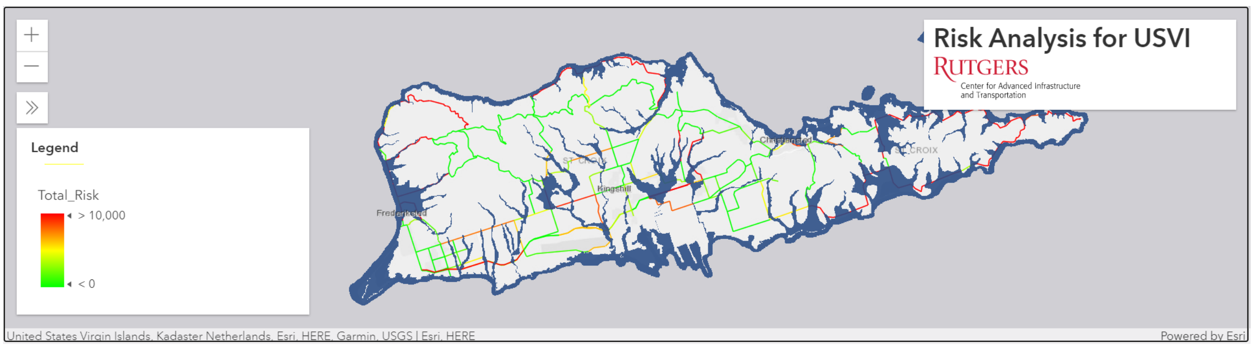
In adapting to and mitigating natural hazard risk, adapting material and design choices to build asset and community resilience could yield long-term cost savings as well. From our study of post-Irma and -Maria pavement in the USVI, we recommend more frequent but less intensive treatments- roadway preservation and rehabilitation- to not only reduce life cycle cost and prolong service life before reconstruction, but also reduce vulnerability to severe rain events and flooding, reducing pavement permeability by sealing cracks. Studying changes in pavement material, design, and construction to mitigate saturation impacts on strength and deterioration could result in better performance and asset resilience in the long run. In addition, taking advantage of technological innovations in data collection and information systems can aid in reducing costs by lightening workloads, enabling easier infrastructure system management, and supplementing limited and expensive equipment. Lastly, dedicated programs for hazard preparedness and response, on top of previously mentioned dedicated resilience planning initiatives, could be useful in building system and community resilience against natural hazard events. Similar reevaluations and improvements in practice to adapt to and mitigate risks, especially in critical and economically significant corridors, will help lower life cycle costs, extend service life and performance, and ensure more reliable, resilient transportation systems alongside risk-conscious TIAM programs for operations and system planning.

## 4.3 Integrated Web Tool Introduction

The final product of this study is a scalable and customizable GIS-based web application for users to visualize and make comparative analyses of investment scenarios, providing a better look at the outputs of the risk-based TIAM framework we developed on a greater scale. After aggregating all relevant data, as desired by the user, the combined dataset can be input to produce a map view reporting road segment attributes and network resilience in colored scales. The user, such as an agency exploring risk management and investment options, can then update global and scenario parameters (e.g., vehicle running costs and pavement condition rating threshold for rehabilitation treatments) and see the resulting output vulnerability values and risk costs. When used with our USVI case data, the tool was able to display expected road network conditions for each of our 5 hypothetical intervention scenarios, as well as predicted roadway inundation lengths and detour distances and times in the event of flooding. The platform is planned to incorporate sea level rise as a risk, superimposing raised water levels onto the map, and can be customized for more natural hazards and asset types. This comparative tool can vastly simplify risk-integrated decision-making processes for both operational and capital investments, providing an interactive network-wide view of strategy impacts.

The tool is developed based on USVI data and can be adapted to other regions. The key features are listed below:

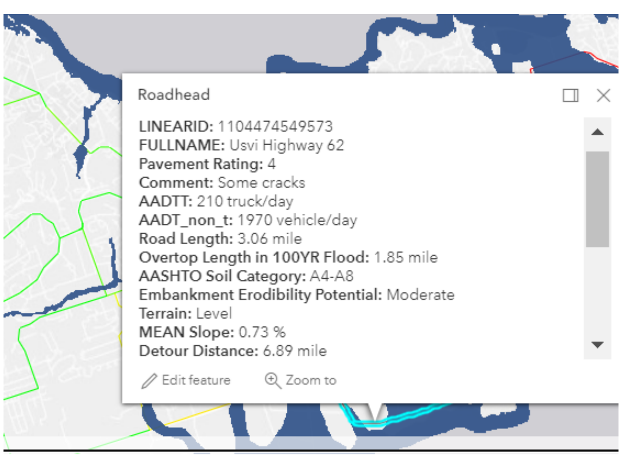
- Flood risks for all segments in the roadway network can be estimated with and without considering future sea level rise scenarios
- Output risk levels are shown on the map by three color scales
- Detailed input data and output risk values are shown on the road info page by clicking on/selecting the specific segment
- Input parameters that are specific to each road segment can be changed within the roadway info page
- Global parameters can be updated all at once across the network
- Complete dataset including output risk values can be exported in html and csv format



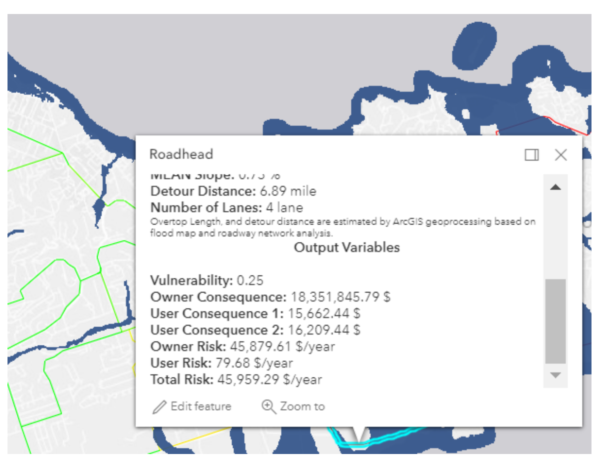

FeatureSharingDraft - STJ Mastersheet (Features: 33, Selected: 0)

| FULLNAME | AADT Truck | AADT Vehicle | MEAN Slope % | Comment | Rating |
|---|---|---|---|---|---|
| Southside Rd | 510 | 3,350 | 2.344 | | 5 |
| Usvi Highway 20 | 150 | 500 | 2.235 | 3906 | 5 |
| Centerline Rd | 270 | 1,690 | 1.651 | Raveling and cracking. | 3.5 |
| Usvi Highway 20 | 150 | 500 | 2.31 | 3920 | 5 |
| Kings Hill Rd | 170 | 420 | 3.502 | | 3 |

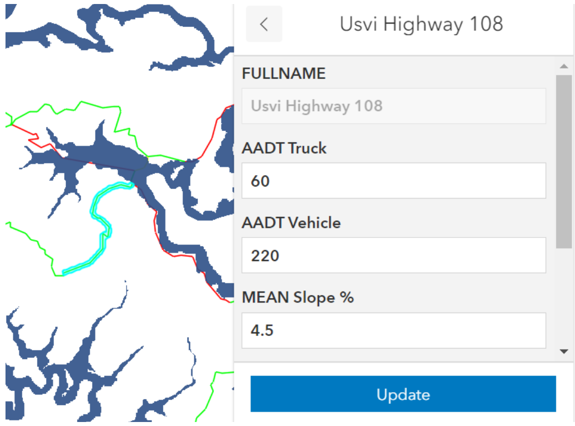
**Figure 49**: Web tool USVI risk analysis map and road attributes table




(a)




(b)




(c)

**Figure 50**: Web tool selected individual road segment (a) editable input parameters and attributes, (b) output risk values and (c) asset specific parameter update page


**Figure 51**: Web tool global parameters and network-wide update capability

## 4.4 Greater Implications: User, Agency, and Macroeconomic Benefits of Risk-Integrated TIAM Framework Implementation

Our framework and tool can help provide insight into how operational and capital spending can be best directed through LCCA/LCP and BCA, as demonstrated with our USVI modeling. Cost-effective approaches for maintenance and investment can be identified by comparison with proposed strategies, making the most out of agency and DOT budgets. With EIA incorporated, agencies can also strategically allocate the resources available to them to produce maximum user and community benefit, including increased economic activity and output, safety improvement, and resilience against natural hazards. This can boost local and state economies, reduce damage and costs of wear and tear and vehicle accidents, and minimize losses while ensuring rapid emergency responses and transportation network reliability after a natural hazard strikes. Having this systematic approach that takes risk into account means publicly funded agencies can serve the public more efficiently, and users can expect more reliable transportation infrastructure where it is felt the most, reducing costs and risk for all.

Just as logical, risk-conscious management of transportation agency resources will have profound benefits for users and the economy, failing to maintain transportation infrastructure in good condition will produce significant financial and economic challenges. According to a 2020 EBP Consulting study for the American Society of Civil Engineers, suboptimal conditions in roads, bridges, and tunnels across the United States are predicted to cause $217 billion in direct costs to households and $1.75 trillion to businesses if unimproved through 2039 (p. 21). Beyond the direct increased costs of greater (idling) fuel usage, lost productive time due to detours and congestion, and increased maintenance costs for wear and tear, further costs are passed around sectors of the national economy particularly due to costlier shipping and supply chains. As noted by EBP Consulting, freight transport is expected to keep growing in the U.S., from "almost 12 billion tons of cargo at an average distance of 174 miles per ton" to 15.5 billion at an average 195 miles per ton, especially with the growth of more time-sensitive supply chains and systems relying on "just-in-time" deliveries (p. 14). With increased congestion and detours due to more intensive interventions, operating costs for logistics operators (such as truck operator expenses and late or unreliable delivery losses, among all the above direct increased costs) will similarly increase, and the study expects that passed-on costs will harm many other sectors and their consumers. The macroeconomic cost of subpar surface transportation is estimated to be $6.22 trillion in national economic output and $2.8 trillion in GDP through 2039 (p. 23); a $1.8 trillion drop in personal consumption is expected due to spending on mitigating extra costs such as increased vehicle wear and tear or fuel use (due to delays and detours), reducing household disposable incomes and consumer spending to impact all economic sectors even further (p. 26). These cascading losses underscore the importance of maintaining and building reliable infrastructure systems, so that both user travel and freight shipping are not made riskier or costlier in time and money. Effective interventions to build resilience and produce cost savings over an asset's life cycle will build the resilience and reliability of entire transportation systems that local and greater scale economies depend on. By standardizing TIAM procedures in a framework that takes risk and resilience into account, beyond qualitative guidelines and principles or standalone analysis, human and economic losses as well as agency and user costs can be minimized in a strategy within managers' financial capabilities, producing lasting economic impacts and community improvements.

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