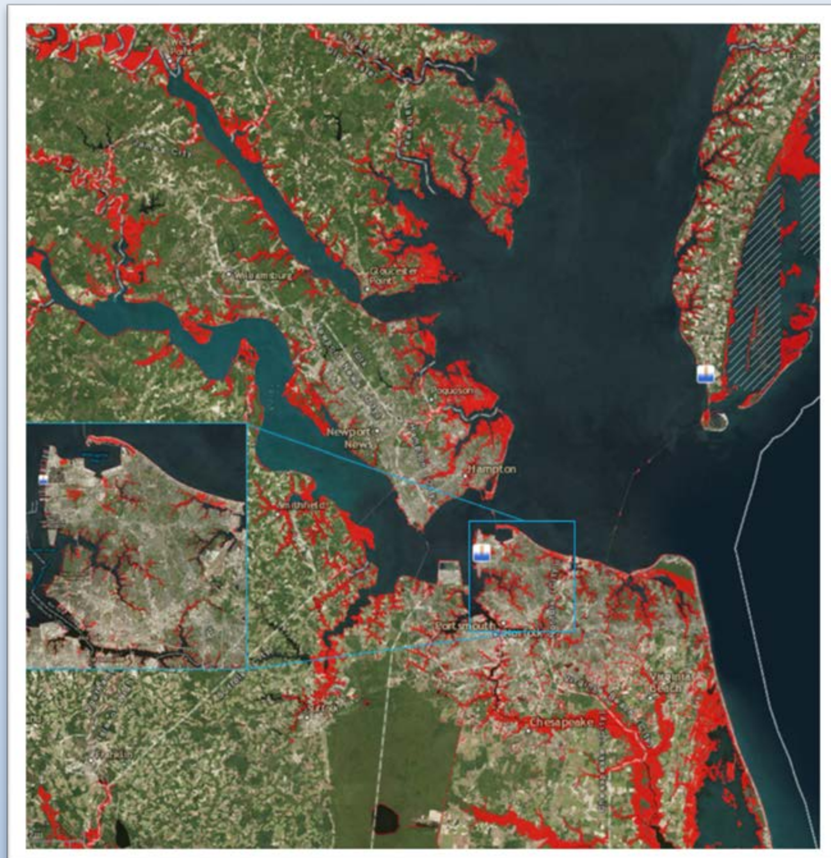
Hampton Roads
Climate Impact Quantification Initiative

Baseline Assessment of the Transportation Assets &
Overview of Economic Analyses Useful in Quantifying Impacts



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U.S. Department of Transportation
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John A. Volpe National Transportation Systems Center

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13. ABSTRACT (Maximum 200 words)

The Hampton Roads Climate Impact Quantification Initiative (HRCIQI) is a multi-part study sponsored by the U.S. Department of Transportation (DOT) Climate Change Center with the goals that include developing a cost tool that provides methods for voluntary grantee consideration of financial impacts in infrastructure planning due to climate change and severe weather. This Baseline Study, conducted in collaboration with several DOT modes, and based on extensive consultation with regional governmental, military and industry stakeholders, summarizes available data, methodologies, and tools to inform a robust analysis of the economic impacts of climate change and severe weather-related disruptions on the region's transportation infrastructure. DOT chose to study the Hampton Roads region based on its unique attributes, including its: extreme vulnerability to sea level rise impacts, that is beginning to threaten transportation system and military operations; strategic significance as home to the nation's largest concentration of federal facilities, including the world's largest naval station; and the partnership opportunities afforded through the Intergovernmental Pilot Program and its partner's deep expertise in analyzing and addressing these impacts. DOT is intending to conduct follow-on work building on this Baseline Study.

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Acknowledgments

This Baseline Assessment of the Transportation Assets in Hampton Roads and Overview of Economic Analyses Useful in Quantifying Assets (Report) of the Hampton Roads Climate Quantification Initiative (Initiative) was developed through a collaborative process that included the active participation from experts from government, academia, and industry. DOT and the authors would like to acknowledge many organizations and individuals that contributed to the development of this report and wish to emphasize this list does not include everyone who assisted.

Leadership of the U.S. DOT Climate Change Center and Environmental Forecasting (Center) has been instrumental in spearheading and coordinating this Initiative, including co-chairs Alasdair Cain and Camille Mittelholtz, Art Rypinski, Eric Weaver, and Core Team leaders Peter Chipman and Shawn Johnson who supported development of the Initiative's design. The Initiative has drawn from the considerable intellectual resources of the Hampton Roads Intergovernmental Pilot, coordinated by Old Dominion University (ODU). We would like to recognize the following individuals from ODU: Captain Ray Toll U.S. Navy (ret.), Director for Coastal Resilience Research, ODU; Rear Admiral Ann Phillips, U.S. Navy (ret.) for helping to explore quantification through her leadership of ODU's Infrastructure Working Group; and Professor Larry Filer for his support through his leadership of the Economic Impact Working Group. Steve Kolk, Assistant Vice President of Pricing American Integrity Insurance Company, also provided an invaluable actuarial industry perspective on the topic.

Over 360 comments were received on the first draft of this report from government, academic and industry experts. We would like to thank the following organizations for their review: Department of the Interior, U.S. Navy, Virginia DOT, Hampton Roads Sanitary District, Virginia Maritime Association, Hampton Roads Planning District Commission, and Hampton Roads Transportation Planning Organization. We also thank Henry R. ("Speaker") Pollard, V, a Partner with the law firm of Williams Mullen, Richmond, Virginia, and Chair of its Coastal Flooding and Resiliency practice group, for his explanation of the interests and concerns of private and public property owners associated with transportation right-of-ways. We would also like to thank Federal Highway Administration (FHWA) staff, both at Headquarters and within the Richmond, VA Division Office, for their significant contribution to the review process, including Becky Lupes, Mack Frost, April Marchese, Virgil Pridemore, Joe Krolak, Brian Beucler, Gerry Solomon and Janet Myers.

EXECUTIVE SUMMARY

The Department of Transportation (DOT) Climate Impact Quantification Initiative study (DOT Quantification Initiative or "Initiative") summarizes available data, methodologies, and tools to inform a robust analysis of the economic impacts of climate change and severe weather-related disruptions on the Hampton Roads (HR) region's transportation infrastructure. Based on extensive stakeholder involvement, this assessment focuses both on the HR region and the City of Norfolk. First, the effort was scoped and established in conjunction with, and supported a broader effort by the HR Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project (IPP HR Pilot) convened by Old Dominion University (ODU), Norfolk, VA. Second, the study will support ongoing efforts by DOT to collaborate with federal, state, and local transportation officials, including industry, to adapt to future impacts in the HR region due to climate change and severe weather.

This study also addresses the interdependency of the transportation network with the broader regional economy and related critical assets and functions, including military preparedness, emergency response and utilities.[1] The HR region, home to the nation's largest concentration of federal facilities, including the world's largest naval station, Naval Station Norfolk, is highly vulnerable to sea level rise, which is beginning to threaten the multi-modal transportation infrastructure and military operations. While not all functions and assets can be quantified, their value is significant to the public, governments and industry.

The established method for measuring risks uses the combination of the probability of the event occurring and the associated consequence of the event. Understanding system vulnerabilities to climate change requires assessing climate-related threats and identifying infrastructure vulnerabilities to those threats. Adaptive measures for reducing identified vulnerabilities can then be considered. Understanding the costs of disruption to the economy (monetized or not) is an important consideration for evaluating adaptive measures. For the quantification of the costs of damaged transportation assets and loss of use of transportation service, the same process can be applied.

This study complements and builds upon other DOT assessments, including the Gulf Coast Studies. Such studies have traditionally focused on the vulnerability of transportation assets to flooding, sea level rise, and storm surge, though some DOT FHWA pilots have augmented such assessments with economic analyses comparing a "do-nothing" scenario against possible

[1] The HR pilot, convened by Old Dominion University, is unrelated to the 2012 VDOT HR Pilot funded by the Federal Highway Administration.

adaptive strategies. A few pilots also considered indirect social, environmental, and economic impacts to varying degrees. For example, the DOT Hillsborough pilot estimated economic losses associated with business and truck delays, lost trips, and vehicle operating costs over a five-day period after a storm event based on the disruption of specific vulnerable transportation facilities. However, these analyses, while useful to considering cost-effective strategies for a given asset, have not to date considered the full range of economic impacts, such as expansive indirect costs, due to transportation disruption.

Within the HR region, there have been a number of analyses considering the potential climate vulnerabilities within the transportation system. These analyses largely focus on flooding impacts related to sea level rise, heavy precipitation events, and storm surge. In addition, a few studies have further considered the economic consequences of storm events. However, similar to the DOT studies summarized above to date, such studies have not considered the "full cost" of future climate-driven storm events that includes both the direct transportation costs (e.g., damaged or destroyed assets) as well as the indirect economic costs as a consequence of loss of transportation services. This report fills an important gap by accounting for indirect losses due to business interruption and loss of earnings, loss of insurance protection due to frequency of disruption, and amplified effects of poverty. This report, through an extensive consultative process that leveraged a wealth of local and regional expertise, assesses the available building blocks and methodologies to conduct such a comprehensive analysis on the HR region.

The structure of this report includes: (1) a summary of the current state of knowledge to inform an analysis for quantifying economic costs of climate change; (2) descriptions of economic methodologies currently in-use by USDOT and resources available for assessing assets and monetizing impacts; and (3) a roadmap of possible steps for conducting a comprehensive economic quantification in HR.

SUMMARY OF FINDINGS

Part 1 considers the available data and information for Hampton Roads that are necessary for this economic analysis.   Transportation Asset Inventory and Data for Economic Analysis

- Overall, there is significant data for bridges and roads, followed by sea ports/waterways, and airports. There is less information for tunnels, railroads and pipelines. However, the National Tunnel Inventory (NTI) will in the coming years provide additional information describing tunnel inventory, use, and condition. Valuation information for tunnels, bridges, and roads includes depreciated values and replacement costs; while valuation information for sea ports/waterways and airports only considers revenue (see Figure SF-1; see Section 1-1).
- Light Detection and Ranging (LiDAR) data collected from 2011 to 2014 provides elevation data useful for understanding asset exposure to flooding. GIS shapefiles have been developed for roadways and elevated roadway structures (e.g., bridges). Additional effort would be required for similar processing of railroads.
- There is minimal information concerning asset condition (see Section 1-1).
- There is some valuation information available; however, much of it is simply the past project cost of constructing the asset or revenues associated with operations (e.g., airports) (see Section 1-1).

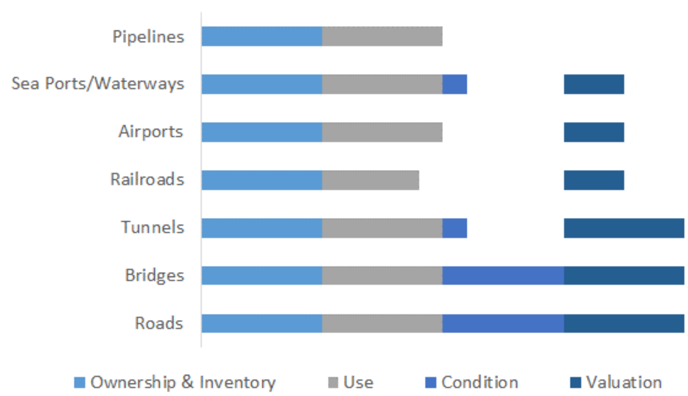

Figure SF-1. Qualitative description of data identified by transportation asset type and described in this report

Indirect Consequences

- There are significant economic consequences for transportation failure, reduced services, and/or implementing adaptive strategies. Data considering these indirect impacts include business interruption and costly consequences for utility services/assets. In addition, there are concerns of social vulnerabilities where certain populations may be more affected. Data are available that identify key economic sectors in the region, critical infrastructure facilities, and indices describing social vulnerabilities (See Section 1-2).

Exposure

- HR is exposed to a number of weather- and climate-related events including sea level rise, storm surge, heat events, and heavy precipitation. All of these stressors are projected to increase to some degree in the coming decades (see Section 1-3).
- Two studies in the HR region have recently been completed that identify transportation asset exposure to sea level rise and storm surge, and consider broader system vulnerabilities (see Section 1-3).

Impact Analysis

- There was no available information or databases describing sensitivities to extreme weather events. Because of this, this study: (i) identified historic storms that caused significant damage and considered associated impacts with an emphasis on transportation assets; (ii) reviewed and presented past impact studies for HR. Hurricanes/tropical storms and nor'easters were the storm events that caused the greatest storm-induced damages (see Section 1-4).
- Three studies considering sea level rise and storm surge identified sector vulnerabilities including transportation within HR and, in some cases, provided monetized values of the impacts (see Section 1-4).

Adaption

- There are a number of adaptation efforts that have been evaluated or are underway in HR. Though many of these efforts are not specific to transportation, this information provides insights of proposed projects that may affect transportation impacts and a reference for related project costs. This information is helpful in understanding potential costs if such strategies were considered in an economic analysis in areas where vulnerabilities may be affected/introduced/alleviated by the adaptation project (see Section 1-5).

Quantifying Cost Burdens

- There are a number of challenges regarding quantifying the cumulative costs of such low-impact/high probability stressors such as recurrent flooding. For high-impact/low probability events, there is concern the costs may fall largely on the taxpayer (see Section 1-6).

Part 2 provides an economic primer illustrating the current methodologies used by the Department of Transportation (DOT), Federal Highway Administration (FHWA). Many of these methodologies (e.g., Life-Cycle Cost Analysis (LCCA), Benefit Cost Analysis (BCA), etc.) do not consider the possible indirect impacts as discussed above. This section considers ways to incorporate such costs. In addition, available tools are considered for their usefulness. Overall, there is not one tool that has been developed that can be used "as is" for this analysis.

Part 3 crosswalks the findings of Part 1 and Part 2 to provide a roadmap of possible steps for conducting an economic quantification in HR.

INTRODUCTION

The Hampton Roads (HR) region, highly dense in transportation infrastructure, is one of the most vulnerable regions to flooding in the nation. Since 1997, extreme weather events have caused havoc across the HR region, causing more than $800M dollars in property damage.[2] The greatest monetized property damage was caused by hurricanes and flood events. These events have also significantly affected the transportation and energy sectors. In addition, recurrent "nuisance" flooding has increased dramatically in recent years and have caused large disruptions to regional transportation networks.[3] There is growing concern that given changes in climate and land-use, the impacts of these events and their impacts will increase. Of particular concern to the Hampton Roads region are sea level rise, storm surge, and heavy precipitation. Projections suggest these climate-related stressors will increase in frequency, magnitude, and/or duration. This report lays out the building blocks of the data and resources available for conducting an economic quantification of the climate-related impacts, such as disruption, on HR's transportation system.

> *The Hampton Roads area in Virginia is experiencing the highest rates of sea-level rise along the entire U.S. East Coast. The area is also second only to New Orleans, LA, as the largest population center at risk from sea-level rise in the country.*
>
> Source: WRI (2014).

> **DOT Terminology**
>
> **Resilience**: The ability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment.
>
> **Exposure** refers to whether the asset or system is located in an area experiencing direct impacts of climate change.
>
> **Sensitivity** refers to how the asset or system fares when exposed to an impact.
>
> **Adaptive capacity** refers to the system's ability to adjust to cope with existing climate variability or future climate impacts.
>
> **Vulnerability:** In the transportation context, it is a function of a transportation system's exposure to climate effects, sensitivity to climate effects, and adaptive capacity.
>
> Source: USDOT FHWA (2012a).

DOT has recently contributed to studies in HR regarding the impact of climate change and extreme weather through conducting a pilot assessment (2011).[4] In addition, from 2014-2016, a representative from DOT's Climate Change Center participated in the HR Intergovernmental Planning Pilot (IPP) convened by Old Dominion University as member of the Working Groups on Infrastructure and Economic Impacts WG. During the IPP process, which was attended by transportation and planning experts and local governments (see text box, below), DOT recommended creating a tool to quantify transportation impacts, and the idea was endorsed. Specifically, in its 2015 report, the IPP stated: "There are

[2] Based on our analysis using the NOAA Storm Event Database.
[3] Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project (2015).
[4] HRTPO (2013b).

significant data gaps that need to be addressed with respect to Economic Modeling in Phase II [of the Pilot] and beyond. For instance, the IWG has concluded that any planning activities taken to address infrastructure need to address the cost and benefits of proposed actions to aid in decision-making."[5] In May 2016, DOT helped organize, with the HR IPP, and participated in a workshop on economic quantification attended by over 50 governmental, academic, and industry parties where DOT presented a draft of this report and sought comment. During its presentation on the draft Quantification Report, DOT explained that its objective, in concert with HR stakeholders, was to develop a cost tool that could, among other things, provide methods for voluntary grantee consideration of financial impacts in planning due to climate change and severe weather.[6] DOT continued to work with the IPP and others to further refine this report through formal and informal consultation, as summarized in the text box, titled Outreach and Collaboration in Hampton Roads: The "Whole of Government" Approach.

A number of entities were involved in HR's Intergovernmental Planning Pilot (see textbox below). The IPP has adopted an overall framework for assessing the risk/vulnerability of transportation assets to climate change and extreme weather that is used throughout the planning community:

- Develop an inventory of the transportation network and assets;
- Identify current and future climate hazards and stressors;
- Characterize risks/vulnerabilities that threaten assets and system functions;
- Identify initial adaptation strategies;
- Integrate strategies into system operations and implementation planning processes;
- Monitor, assess performance, and revise risk/vulnerability scenarios and adaptation strategies.

These steps closely follow the Department of Transportation's (DOT) Federal Highway Administration (FHWA) Framework for Climate Change & Extreme Weather Vulnerability Assessment (see Figure 1). This framework encapsulates much of the common elements followed by many agencies when conducting a risk/vulnerability assessment. These steps can be applied at various scales within the region's transportation system (e.g., across all nodes of transport or drilled down to a specific asset class within the study region). There are a few economic entry points into this framework, specifically including: (1) considering asset criticality; (2) considering the economic consequences of climate-related events; and/or (3) the implementation of adaptation strategies.

[5] Hampton Roads Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project (2015).
[6] Old Dominion University et al. (2016).

Outreach and Collaboration in Hampton Roads:
The "Whole of Government" Approach

DOT's approach to scoping the project involved intensive consultations with participants in the Hampton Roads Intergovernmental Pilot Project (IPP) over a two-year period. The DOT supported the Infrastructure Planning Working Group and Economic Impact Advisory Committee through monthly in-person meetings. It worked with HR planning agencies—Hampton Roads Planning District Commission (HRPDC), Hampton Roads Transportation Planning Organization (HRTPO), Virginia DOT, and municipal and state government entities. The process, convened by Old Dominion University, has been dubbed a "whole of government" approach.

DOT also presented at the following forums:

Alasdair Cain, Co-Chair, DOT Climate Change Center, Collaborations and Community Resilience Conference, ODU, Federal Panel with Cap. Pat Rios, Comm Officer, Naval Facilities, Middle Atlantic, U.S. Navy Rebecca Patton, Climate Change Adaptation Integration, U.S. DOD (December 10, 2015).

Alan Strasser, Steering Committee, DOT Climate Change Center, Bahar Barami, Economist, Volpe Center, The Economic Impacts of Sea-Level Rise in Hampton Roads: An Appraisal of the Projects Underway. Old Dominion University, Virginia Modeling and Simulation Center, Suffolk, VA (May 18, 2016).
In addition, DOT participated in additional stakeholder discussions to solicit information and feedback:

Alan Strasser, Project Coordinator, DOT Climate Change Center, Rawlings Miller, Climate Resilience Specialist, Volpe Center, Bahar Barami, Economist, Volpe Center, David Arthur, Branch Chief, Volpe Center, Kristin Lewis, Environmental Scientist, Volpe Center, Alasdair Cain, Co-Chair, DOT Climate Change Center, Shawn Johnson, DOT Climate Change Center, Meeting at Hampton Roads Transportation Planning Organization and Hampton Roads Planning District Commission, Chesapeake, VA (July 7, 2016).

Alan Strasser, Project Coordinator, DOT Climate Change Center, Rawlings Miller, Climate Resilience Specialist, Volpe Center, David Arthur, Branch Chief, Volpe Center, presented Hampton Roads Climate Impact Quantification Initiative. Transportation Technical Advisory Committee (TTAC), Chesapeake, VA (September 7, 2016).

Alan Strasser, Project Coordinator, DOT Climate Change Center, Rawlings Miller, Climate Resilience Specialist, Volpe Center, David Arthur, Branch Chief, Volpe Center, presented Hampton Roads Climate Impact Quantification Initiative. Virginia Maritime Association, Norfolk, VA (September 7, 2016).

[1]A partial list of stakeholders involved in the HR Pilot include: Hampton Roads Transportation Planning Organization; Virginia DOT, Hampton Roads Planning District Commission, City of Norfolk, City of Virginia Beach, City of Newport News, and the U.S. Navy. For more information on the Pilot, including its Phase I report of 2015, see: http://www.centerforsealevelrise.org/research-resources/pilot-project-resources.

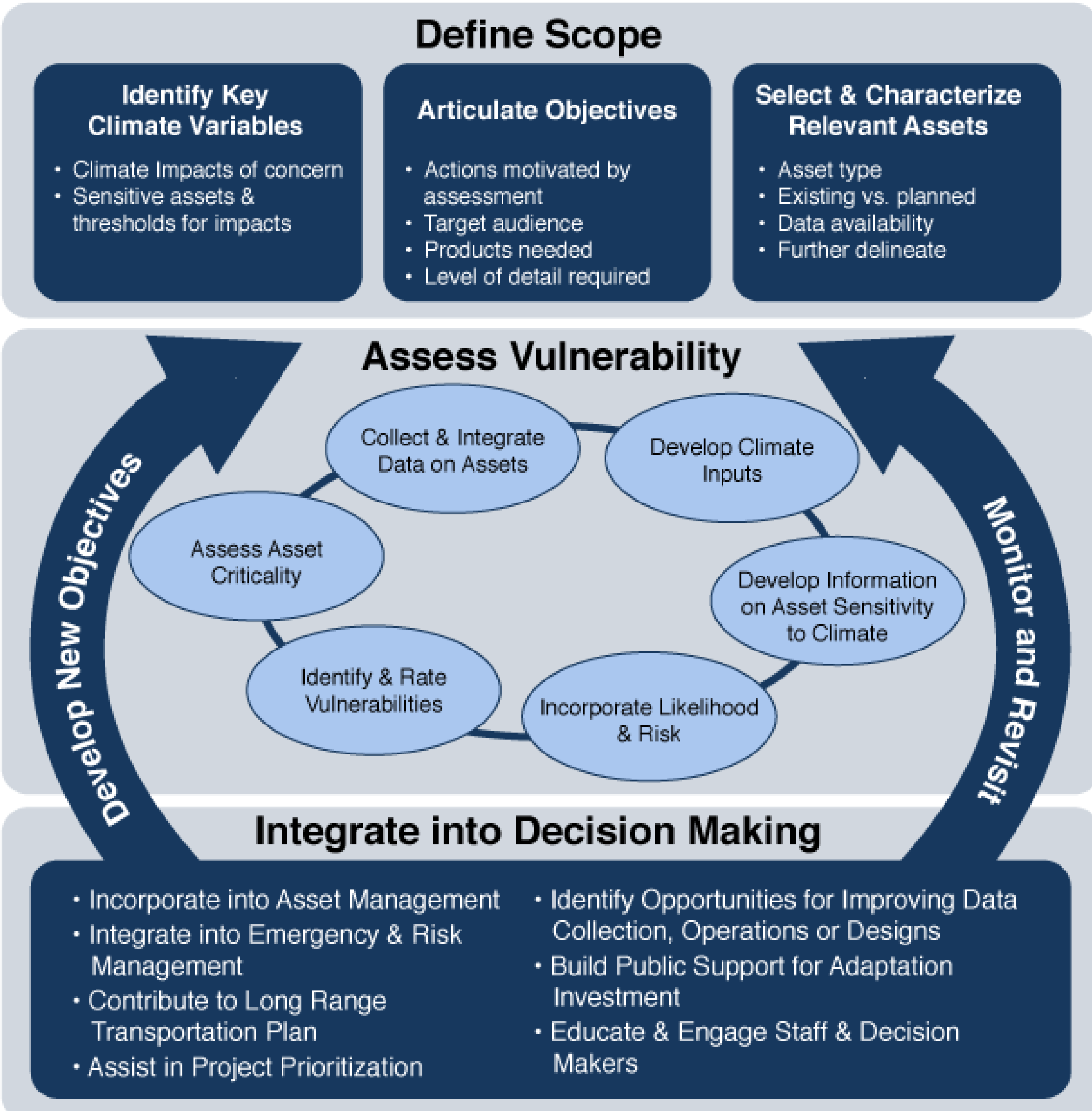

Figure 1. DOT FHWA Framework for Climate Change & Extreme Weather Vulnerability Assessment (Source: USDOT FHWA (2012a))

Zooming down to the facility-specific level, Department of Transportation (DOT) Federal Highway Administration (FHWA) developed an 11-Step Process for conducting a facility-specific[7] assessment and developing adaptation strategies.[8] This approach can be implemented, e.g., once a critical asset has been identified as vulnerable, following the steps as provided in the textbox entitled, *The Process*. Step 8 outlines a methodology for conducting an economic analysis which evaluates how benefits of implementing an

[7] Examples include pavement, bridge, and flood protection.
[8] USDOT (2014a).

adaptation strategy (i.e., costs avoided) compared to the incremental costs under each possible future climate scenario.

The Process

1. Describe the site context;
2. Describe the existing/proposed facility;
3. Identify climate stressors that may have an impact infrastructure components;
4. Decide on climate scenarios and determine the magnitude of changes;
5. Assess performance of the existing/proposed facility;
6. Identify adaptation option(s);
7. Assess performance of the adaptation options;
8. Conduct an economic analysis;
9. Evaluate additional decision-making considerations;
10. Select a course of action;
11. Plan and conduct ongoing activities.

Source: USDOT (2014a).

However, what is missing from both the framework and facility-level approach described above is a means to consider the overarching economic consequences associated with transportation loss that affect the region both during and after the storm event and contribute to comparing the economic costs and benefits of possible adaptive measures. By including such considerations, this study will create pathways within the DOT FHWA Framework for integrating economic consequences into "smart" decision making; i.e., without including these potentially larger economic impacts, the decisions reached are based on a somewhat myopic analysis. For example, we need to quantify climate-related losses associated with the costs of social vulnerabilities to capture the extent of direct and indirect losses that arise from poverty, lack of transportation access, business interruption costs not captured as direct property losses, and the difficulty of assigning ownership rights to damaged property to allocate the responsibility for paying for the costs. Underscoring the sharp contrast between direct and total costs of a climate-related incident is a recent study by Sandia National Laboratories that estimated the potential range of "direct" economic losses from a 4-day flooding/SLR in Norfolk to range between $27M to $57M (depending on the SLR severity scenario).[9] However, the study found that direct losses accounted for only 38 percent of the total costs. When "indirect" costs that accounted for the remaining 62 percent of the total damage costs were added, Norfolk's total losses from a 4-day business interruption costs would escalate to between $70M and $145M.

This report surveys available information, data, and resources that may inform such an overarching economic analysis. The report is divided into three parts:

- **Part 1: Baseline Assessment**: Describes the available data and information useful for conducting a climate-related economic analysis.
- **Part 2: Overview of Economic Methodologies and Resources for Assessing Transportation Vulnerabilities and Quantifying Economic Impacts Related to Climate Change**: Provides a primer of economic methodologies useful to consider for this work along with available vulnerability and economic tools and resources.

[9] Sandia National Laboratories (2013).

- **Part 3: Conducting an Economic Quantification Study in Hampton Roads**: Presents a roadmap for a regional economic analysis based on the findings of Part 1 and Part 2.

METHODOLOGY

This analysis incorporates best available data—including Federal databases and publicly available reports and research findings—for developing a high-level initial baseline inventory of HR transportation assets at risk from climate change disruption (see Table 1). In addition, this analysis includes economic impact assessment tools and methodologies available for quantification of the economic costs of climate change. Unless otherwise noted, the dollar values are presented as nominal values as provided by the cited source (i.e., not adjusted to 2016 values). Many other public and academic studies and data sources have also been consulted, and stakeholder contributions were invaluable to this analysis. Appendices B and C provide the study references and an inventory of data sources consulted for this report. This information was collected by conducting a targeted literature search and through stakeholder participation. Interviews, conferences, and other forms of communications were conducted with Hampton Roads Transportation Planning Organization (HRTPO), Hampton Roads Planning District Commission (HRPDC), DOT FHWA Virginia Division, Virginia Department of Transportation (VDOT), Old Dominion University (ODU), United States Army Corps of Engineers (USACE), Virginia Maritime Association, among others. In addition, DOT held a spring workshop to present and discuss ongoing and upcoming climate-related economic analysis in HR.

Table 1. Summary of the data/resources and providers of reports used in this analysis

DATA / RESOURCES	REPORTS PREPARED BY
• FEMA HAZUS-MH • NATIONAL ATLAS DATABASE • NATIONAL BRIDGE INVENTORY (NBI) • NOAA NATIONAL CLIMATE DATA CENTER (NCDC) • UNIVERSITY OF SOUTH CAROLINA SHELDUS	• Hampton Roads Partnership • Hampton Roads Planning District Commission (HRPDC) • Hampton Roads Transportation Planning Organization (HRTPO) • Old Dominion University (ODU) • Sandia National Laboratories • US Department of Transportation (USDOT) • United States Army Corps of Engineers (USACE) • Virginia Department Of Transportation (VDOT) • Virginia Institute of Marine Science (VIMS)

STUDY AREA

This study adopted the Hampton Roads District Commission's definition of HR.[10] The HR[11] region, is spread over 16 jurisdictions, including 10 cities and 6 counties. The HR region is a subset of the larger Virginia Beach–Norfolk–Newport News Metropolitan Statistical Area (MSA); (1.64M population), as well as the VA-NC Combined Statistical Area that includes four additional counties in North Carolina, raising the total regional population to over 1.8 million residents.[12] HR cities include: Chesapeake, Franklin, Hampton, Newport News, Norfolk, Poquoson, Portsmouth, Suffolk, Virginia Beach, and Williamsburg. The six counties in HR include: Gloucester County, Isle of Wight County[13], James City County, Southampton County, Surry County, and York County. Unless otherwise specified, most data citations for this report relate to the City of Norfolk or the entire 16-jurisdiction HR. The table below shows the different geographic definitions of Hampton Roads, including the definition adopted in this report.

Table 2. Cities and counties located in HR as defined for the report and other regional definitions presented in this report

COUNTY/CITY NAME	HR AS DEFINED IN THIS REPORT	HRPDC DEFINITION OF HR	HRTPO DEFINITION OF HR	MSA*
CURRITCUK COUNTY, NC				X
GATES COUNTY, NC				X
GLOUCESTER COUNTY, VA	X	X	X	X
ISLE OF WIGHT COUNTY, VA	X	X	X	X
JAMES CITY COUNTY, VA	X	X	X	X
MATTHEWS COUNTY, VA				X
SOUTHAMPTON COUNTY, VA	X	X		
SURRY COUNTY, VA	X	X		
YORK COUNTY, VA	X	X	X	X
CHESAPEAKE, VA	X	X	X	X
FRANKLIN, VA	X	X		
HAMPTON, VA	X	X	X	X
NEWPORT NEWS, VA	X	X	X	X
NORFOLK, VA	X	X	X	X
POQUOSON, VA	X	X	X	X
PORTSMOUTH, VA	X	X	X	X
SUFFOLK, VA	X	X	X	X
VIRGINIA BEACH, VA	X	X	X	X
WILLIAMSBURG, VA	X	X	X	X

* Norfolk-Virginia-Beach-Newport News MSA

[10] HRPDC (2016).

[11] The term Hampton Roads, while connoting the broader Hampton Roads region, actually refers to a body of water called Hampton Roads, is one of the world's largest natural harbors. It incorporates the mouths of the Elizabeth River, Nansemond River, and James River with several smaller rivers and empties into the Chesapeake Bay near its opening to the Atlantic Ocean.

[12] "Metropolitan and Micropolitan Statistical Areas." See: http://www.census.gov/population/metro.

[13] Includes the Town of Smithfield.

This report presents the information at two-scales: (1) HR region as a whole and (2) Norfolk (depending on the context and availability of disaggregated data). In some instances, when the asset dataset being analyzed for this report required significant effort to evaluate, the analysis was curtailed to just the City of Norfolk to provide an example of its usefulness. Norfolk is used as an example because at the onset of the development of this report, the HR Pilot requested that we consider the Pretty Lake neighborhood as a pilot location for later work because of the existing and potentially worsening vulnerabilities to SLR/storm surge. The Pretty Lake neighborhood transects Norfolk and Virginia Beach (see Figure 2).

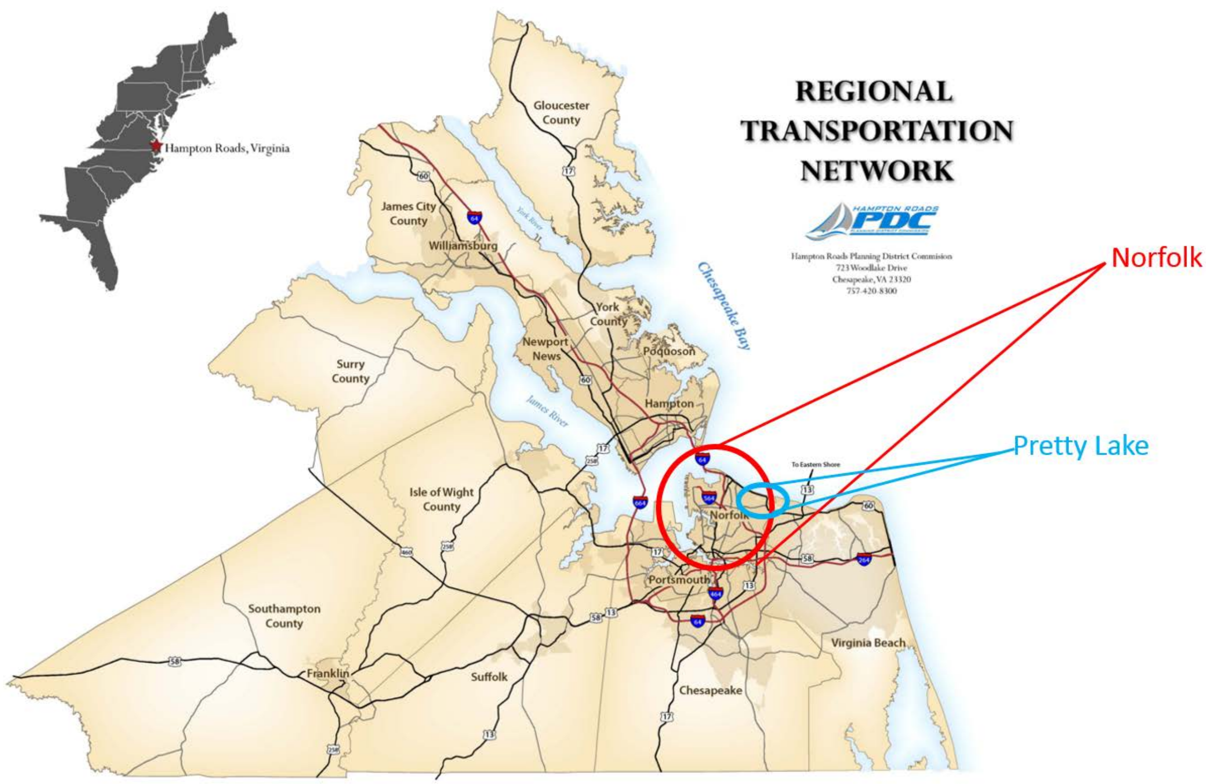

Figure 2. Hampton Roads, Norfolk, and Pretty Lake (Source: HRPDC Maps and GIS)

PART 1 – BASELINE ASSESSMENT

Estimating the economic impacts of climate change involves: estimating the likelihood of disruptive climate-related events; identifying the direct and indirect components of the costs; and crafting strategies that run the gamut from engineered protective measures, to accommodation strategies, to ultimate retreat. This section outlines available data and information to inform:

- Direct economic costs related to transportation loss during an event and asset vulnerabilities when considering asset sensitivities to a future event (Section 1-1);
- Associated indirect economic costs in response to loss of transportation services (Section 1-2);
- Understanding current and future asset exposure to events and two studies that identify transportation asset exposure to sea level rise (SLR)/storm surge (Section 1-3);
- Understanding disruptions during past events and recent studies that quantify climate-related impacts (Section 1-4);
- Costs associated with current or evaluated adaptive measures to curtail event-driven disruptions (Section 1-5);
- Challenges when quantifying the economic costs associated with low-risk/high probability events and the public burden of high-risk/low probability events (Section 1-6).

Each topic is discussed in detail below.

1-1 MULTIMODAL TRANSPORTATION NETWORK DATA

> *Hampton Roads is often described by its leaders as "the most infrastructure dependent-place on the East Coast."*
>
> Remarks by VA Transportation Secretary Aubrey Layne, May 2015; Congressman Randy Forbes (R-VA 4th District), March 2016, and; Norfolk Mayor Paul D. Fraim, February 2012.

This section provides an overview of the HR transportation network by asset- or service-type, with specific focus on HR and Norfolk area, depending on data availability.[14] A sizeable transportation network is located within HR including the Norfolk area, demonstrating the diversity of assets (see Figure 3). The following information is provided with gaps noted: inventory, use, condition, and valuation information (in some instances, revenue information is provided under the valuation category):

- Inventory: Summarizes available information regarding location, ownership, and quantity. GIS data availability is also noted. This is useful when considering criticality and exposure of assets.
- Use: Describes the frequency and type of users served by the asset-type. This is important for understanding criticality of assets and potential implications to the region if service is lost.
- Condition: Describes the condition of the assets. This is useful for understanding the remaining lifetime of the existing asset, the potential need for reconstruction (e.g., funding opportunities

[14] The Pretty Lake neighborhood is not specifically discussed in this section because the databases and information sources found and/or recommended did not disaggregate assets at the neighborhood scale.

particularly if a strategy could be considered as "no regrets")[15], and the possibility of enhanced sensitivities to exposure due to poor conditions.

- Valuation information: Provides data on estimating the construction and valuation costs of an asset and, in some cases, provides revenue information. This is useful in considering direct costs associated with a potential loss of asset.

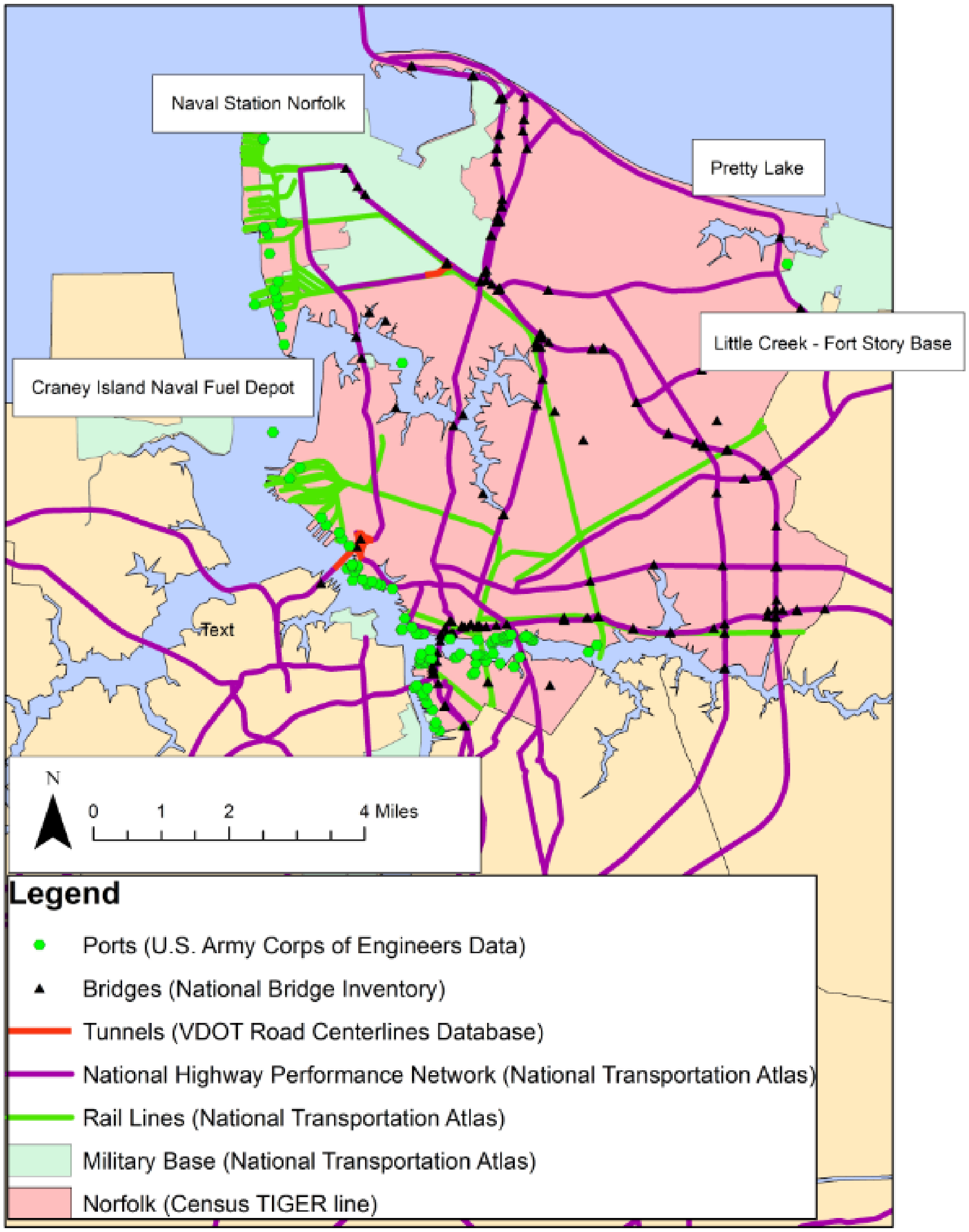

Figure 3. Norfolk highways, bridges, ports, and rail lines (Source: National Transportation Atlas Database (NTAD))

[15] A "no regrets" strategy is one that would be considered regardless of whether extreme events are amplified by climate change.

For this section's discussion on service-types, the operations and use are discussed.

HRTPO Prioritization Tool and Scoring Criteria: Economic Vitality

HRTPO developed a tool for prioritizing possible transportation projects. This tool scores a project based on project utility, project viability, and economic vitality. The criteria used in scoring a project's economic vitality may be useful when considering economic metrics in a regional economic quantification study. These criteria have already been vetted by the region, are familiar to transportation stakeholders, and represent economic drivers in the region. For example, the criteria include whether the transportation facility increases access to the port facilities, tourist destinations, defense installations, and high density employment areas. See Appendix D for additional details.

Source: Adapted from communication with representatives from HRTPO

1-1-1 Asset Categories

Roads

Ownership & Inventory. There are a total of 11,767 miles of roads within HR including 1,094 miles of roads within Norfolk. These roadways include a diversity of centerline data types from interstate highways to base roads on military installations (see Table 3).

Table 3. Roadway centerline miles in Hampton Roads by roadway type (Sources: based on data from HRPDC (2012); Norfolk OpenGIS; per communication with HRTPO representatives)

ROADWAY	OWNERSHIP	FUNDING	HR TOTAL (CENTERLINE MILES)	NORFOLK TOTAL (CENTERLINE MILES)
INTERSTATE	VDOT	Eligible for Federal funding	250	102
PRIMARY	VDOT, VA cities	Eligible for Federal funding	1,460	98
SECONDARY	VDOT, VA cities	Eligible for State and Federal funding	2,216	169
LOCAL OR PRIVATE	VDOT, VA Cities, Federal	Eligible for State funding*	7,841	643
BASE ROADS (MILITARY)	Military		NA	82
TOTAL ROAD-MILES			**11,767**	**1,094**

**Private roads do not receive state funding. To be eligible for state funding, a road must be on a state-maintained road network (this may include local roads in subdivisions). Urban public roads are eligible for state and federal funding.*

HRPTO has produced a GIS shapefile that provides roadway location and road bed elevation useful for identifying roadways that could be submerged under various inundation scenarios.[16] This GIS shapefile was developed based on elevations constructed from Light Detection and Ranging (LiDAR) data and HRPTO GIS road layers.[17] The GIS shapefile is very useful, though there are a few limitations: (1) additional analysis is required to accurately portray roadways constructed at higher elevations, and (2) the centerline of roadways was used to represent the roadways, thereby not capturing roadways that may be partially flooded.

Use. Roads play a critical role in the transport of employees to/from work. Daily vehicle miles traveled (DVMT) in HR was estimated at about 40M in 2011.[18] Spatially, the work-related commuter patterns are complicated, with significant travel across much of the region (see Figure 4).[19] The largest subset of travelers appear to be traveling within the southeastern portion of the region, particularly for travel to/from the Suffolk, Chesapeake, Norfolk, and Virginia Beach cities (thickness of the arrows provide relative measure of the number of travelers compared to other routes).

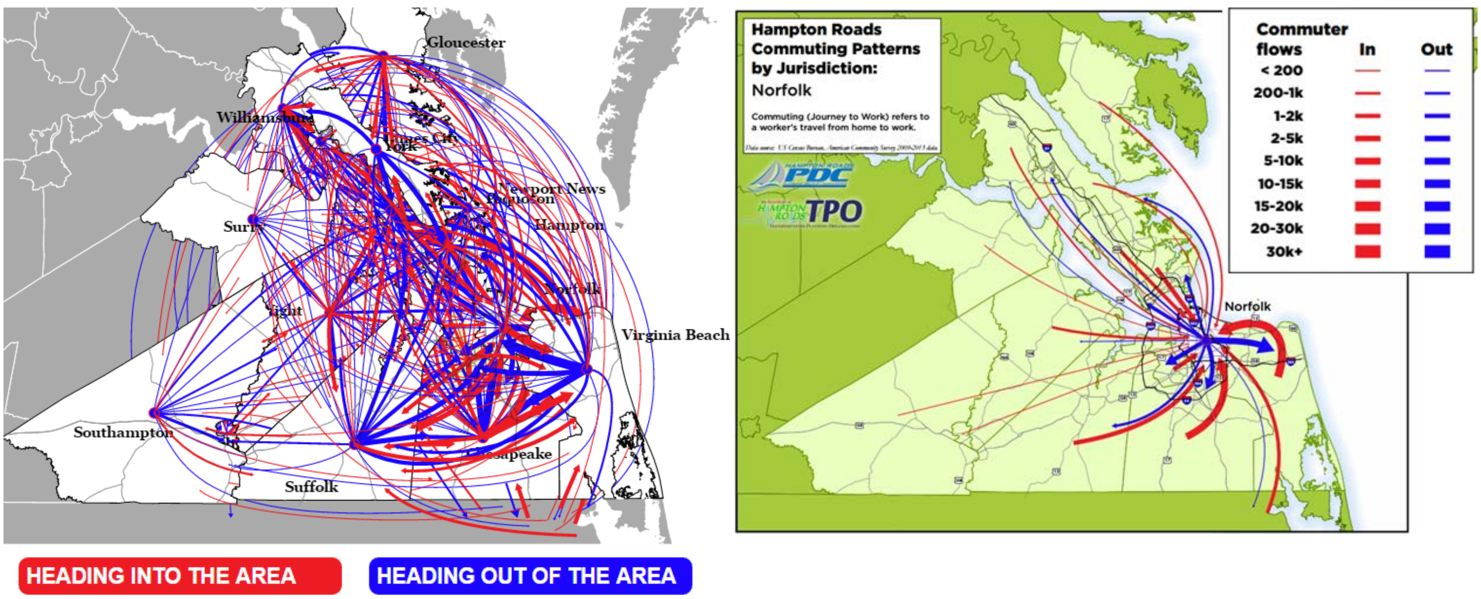

Figure 4. Commuting pathways within Hampton Roads (left panel) and within Norfolk (right panel) (Sources: Hampton Roads Transportation Planning Organization; using 2009-2013 data from U.S. Census Bureau; Hampton Roads Planning District Commission)

The majority of the population commutes for work into Norfolk from communities to the southwest, south, and east of the city. Figure 4 depicts the regional commuting patterns to and from Norfolk, based on data

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[16] HRTPO (2016).

[17] LiDAR data was collected from the region from 2011 to 2014 and referenced against the North American Vertical Datum 1988 (NAVD 88). NAVD88 serves as a reference for measuring elevation. LiDAR provides elevation for bare earth. The GIS elevation has a spatial resolution of 5 feet by 5 feet.

[18] HRTPO (2013a).

[19] Pascale (2016).

from the U.S. Census Bureau in 2009 to 2013.[20] Pretty Lakes, located in western Norfolk and eastern Virginia Beach, represents a significant portion of commuters. However, the longest commutes are traveled by a smaller subset of the population generally to the west and north of the city. The more heavily traveled routes likely require additional maintenance and upkeep, and loss of such routes from extreme weather events will likely have a larger economic impact on the region than the less traveled routes.

Condition. Virginia earned a "D" on the Report Card of America's Infrastructure in 2015.[21] In 2008, 6 percent of major roads were classified as poor, about a quarter were classified as deficient, and 18 percent were considered only mediocre.[22] Over 20 percent of Virginia's roads score lower than a 2.5 on the Present Serviceability Rating, generally regarded as the lowest acceptable road score for comfortable driving.[23] This information is not available disaggregated to the regional or city jurisdictional level.

Congress in the recent law titled, Moving Ahead for Progress in the 21st Century (MAP-21) (Pub. L. 112–141, July 6, 2012) introduced pavement condition metrics for roadways that qualify for federal funding. This covers pavements on the Interstate System and on the non-interstate National Highway System (NHS). The performance measures include roughness, cracking, rutting, and faulting.

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[20] United States Census Bureau, "American Community Survey (ACS)."
[21] American Society of Civil Engineers (2016).
[22] The Road Information Program (TRIP) (2011).
[23] Research and Innovative Technology Administration (RITA) (2011). It costs motorists about $1.8 billion a year to drive on roads that need to be repaired, which equates to $344 per motorist per year. If these roads are repaired or reconstructed (e.g., in response to adaptive measures), the reduction of costs would be a benefit to motorists.

Table 4. Proposed thresholds for pavement condition metrics (Source: FHWA (2013b))

Surface Type	Metric	Metric Range	Proposed Rating
All Pavements	International Roughness Index	<95	Good
		95-170 (under 1 mill pop)	Fair
		95-220 (urbanized, over 1 mill pop)	
		>170 (under 1 mill pop)	Poor
		>220 (urbanized, over 1 mill pop)	
Asphalt Pavement, Jointed Concrete	Cracking %	< 5%	Good
		5-10%	Fair
		>10 %	Poor
Asphalt Pavement	Rutting	<.20	Good
		.20-.40	Fair
		>.40	Poor
Jointed Concrete Pavement	Faulting	<.05	Good
		.05-.15	Fair
		>.15	Poor
Continuously Reinforced Concrete Pavement	Cracking %	< 5%	Good
		5-10%	Fair
		>10 %	Poor

A recent report for the Commonwealth of Virginia analyzed the pavement conditions for VDOT districts, including the HR. [24] Pavement condition is based on the aggregate of a load-related distress rating (e.g., fatigue, cracking, rutting, etc.) and a non-load distress rating (e.g., longitudinal joint separation, etc.) where a value of 60 is considered "deficient" and warrants further evaluation. Pavement roughness is describes as ride quality where values above 140 are considered poor quality for interstate and primary roads and values above 220 are considered poor quality for secondary roads.

Overall, roads in HR were observed to be in relatively good condition. Table 5 shows the percentage of roads that are in sufficient condition (i.e., roads rating at fair or better). Interstates and primary roads exceed the Virginia target of 82 percent, with 91.1 percent and 87.3 percent on pavement condition, respectively. They also exceed the roughness target of 85 percent, with 98.8 percent and 90.4 percent. Secondary roads are in worse condition, though they still exceed the target of 65 percent for pavement condition. There is no target for roughness, but only 58.8 percent of secondary roads are rated fair or higher.

[24] VDOT (2015b).

Table 5. Percent of pavement condition and roughness rated as fair or better for HR in 2015 (Source: VDOT (2015b))

	PAVEMENT CONDITION (%)		PAVEMENT ROUGHNESS (%)	
	HR	Target	HR	Target
INTERSTATE	91.1	82	89.8	85
PRIMARY	87.3	82	90.4	85
SECONDARY	75.9	65	58.8	-

Table 6 provides the number of lane miles that are deficient (i.e. they are rated as poor or very poor) based on scoring of pavement condition and pavement roughness. Interstates have the lowest lane mileage that is deficient, followed by primary, and then by secondary. Note that the numbers for secondary are understated, as they do not include all secondary roads in the region, just a survey of 1,252 miles.

Table 6. Lane miles in HR that scored deficient for pavement condition and pavement roughness in 2015 (Source: VDOT (2015b))

	PAVEMENT CONDITION	PAVEMENT ROUGHNESS
INTERSTATE	70	79
PRIMARY	223	166
SECONDARY*	302	497

**Out of a survey of 1252 miles*

Valuation. VDOT provides recommendations for calculating construction costs of roadways and valuation of existing roadways. The costs of roadways is calculated by multiplying the miles of roadway to be built by the roadway type cost factor. The cost factors are based on valuation in the year 2000. VDOT recommends applying the Bureau of Labor Statistics Consumer Price Index to inflate these costs to today's dollars.[25] The costs per mile range from $237,208 (FY2000) for a secondary roadway to $1,874,055 (FY2000) for an interstate highway (see Table 7). Similar information is not available for estimating the cost to reconstruct roadways. However, such information may be gathered from compiling reconstruction costs associated with past transportation projects.

Table 7. Costs to construct 1 lane mile for various types of roadways (Source: using cost factors from VDOT (2015a))

ROADWAY	AVERAGE COST TO CONSTRUCT 1 LANE MILE (FY2000)
INTERSTATE	$1,874,055
PRIMARY	$768,627
SECONDARY	$237,208
URBAN	$799,775

[25] Bureau of Labor Statistics Consumer Price Index is found here: http://www.bls.gov/cpi/.

VDOT provides a methodology to estimate the valuation of existing roadways. First, determine lane miles by roadway type and year. Second, subtract any lane miles related to bridges and tunnels to obtain the roadway lane miles. Third, for each type of roadway comprised in the roadway lane miles, identify the costs (FY2000) to construct a lane mile of road and apply a deflation factor by year using the Consumer Price Index. For depreciation, VDOT suggests roads have a useful life of 30 years and to apply a straight line depreciation method to estimate value.

Another source of valuation information is FEMA's Hazards-United States Multi-Hazard tool (HAZUS-MH). HAZUS-MH is a suite of three models that estimate losses associated with earthquakes, hurricane wind, and flood. The flood model considers both coastal and riverine flooding. HAZUS-MH includes information concerning transportation lifelines that may be useful for an economic quantification, such as valuation data on roadways. HAZUS-MH data suggests that the total valuation for Norfolk highways is approximately $1.4 billion, with urban principal arterial representing about 60 percent of total valuation (see Table 8). This information can be accessed and analyzed for other regions within HR.

Table 8. Total valuation of Norfolk highways, by category (Source: Hazards United States – Multi Hazard (HAZUS-MH))

ROADWAY	TOTAL LENGTH (CENTERLINE MILES)	TOTAL LANE MILES (MILES)	TOTAL REPLACEMENT COST ($000)
UNKNOWN	10.9	No data	$72,537
URBAN FREEWAY OR EXPRESSWAY	0.3	0.6	$986
URBAN INTERSTATE	41.1	275.5	$470,104
URBAN MINOR ARTERIAL	4.1	14.6	$24,310
URBAN PRINCIPAL ARTERIAL	116.1	229.7	$839,847
TOTAL	**172.4**	**520.3**	**$1,407,784**

Bridges

Ownership & Inventory. The 2012 Hampton Roads Transportation Planning Organization (HRTPO) *Regional Bridge Study* describes the prominent role bridges play in the HR landscape. These bridges range from major spans such as the Coleman Bridge, James River Bridge, and High Rise Bridge, the Interstate system bridges, and many smaller bridges that provide grade separation for principal arterials, and smaller structures such as culverts that span the myriad of creeks, swamps and waterways in the regions.[26] Water divides Hampton

[26] According to the HRTPO (2012b) report*:* HR ranked 21st highest in median bridge age among the 35 comparable area (with population between 1-3 million). Chesapeake, Norfolk, Southampton, Suffolk and Virginia Beach have the largest number of bridges (between 118 and 188 bridges each) with ages around 37 or slightly older.

Roads into many sub-regions, making bridges a prominent feature of the HR landscape, totaling 1,223.[27] Indeed, HR has more lane-miles of bridges than *all* other metropolitan areas in Virginia, and many others nationally.[28]

There are a number of bridge types in HR and Norfolk (see Table 9). HR bridges are largely stringer/multi-beam or girder system bridges (65 percent) (also representing 88 percent of Norfolk bridges). Considering the bridge type is important, as a climate-sensitivity analysis is to determine if the type of bridge introduces specific sensitivities to a changing climate. For example, a storm surge event could damage a movable bridge so that the bridge is stuck in either the open position, halting roadway traffic, or in the closed position, stopping ship traffic.

Table 9. Bridge type and number in HR and Norfolk (based on data from the 2015 NBI)

	HAMPTON ROADS		**NORFOLK**	
STRUCTURE TYPE	# OF BRIDGES	% OF BRIDGES	# OF BRIDGES	% OF BRIDGES
SLAB	99	8.15	4	2.11
STRINGER/MULTI-BEAM OR GIRDER	788	64.91	167	87.89
GIRDER AND FLOORBEAM SYSTEM	7	0.58	-	-
TEE BEAM	39	3.21	1	0.53
BOX BEAM OR GIRDERS – MULTIPLE	48	3.95	5	2.63
BOX BEAM OR GIRDERS - SINGLE OR SPREAD	1	0.08	-	-
FRAME (EXCEPT FRAME CULVERTS)	4	0.33	-	-
TRUSS – DECK	2	0.16	-	-
TRUSS – THRU	3	0.25	-	-
ARCH – DECK	13	1.07	-	-
ARCH – THRU	4	0.33	-	-
MOVABLE - LIFT	3	0.25	-	-
MOVABLE - BASCULE	6	0.49	2	1.05
MOVABLE - SWING	3	0.25	-	-
CULVERT (INCLUDES FRAME CULVERTS)[29]	193	15.90	11	5.79
OTHER	1	0.08	-	-
TOTAL	**1214**		**190**	

[27] HRTPO (2012b). 99 percent of these bridges are captured in the 2015 NBI (i.e., 1,214 bridges of the total 1,223 bridges identified by the HRTPO (2012b) report).
[28] HRTPO (2012a).
[29] The FHWA Recording and Coding Guide defines culverts as "A structure designed hydraulically to take advantage of submergence to increase hydraulic capacity. Culverts, as distinguished from bridges, are usually covered with embankment and are composed of structural material around the entire perimeter, although some are supported on spread footings with the streambed serving as the bottom of the culvert. Culverts may qualify to be considered "bridge" length." The culverts in this analysis are culverts over 20 feet in length.

Within HR, the majority of the 1,223 bridges are owned by VDOT (63 percent) and municipalities (33 percent).[30] VDOT owns and maintains bridges on the Interstate system and those outside of cities. Cities own and maintain bridges located within the city but not located on the Interstate system. A much smaller number of bridges (2.7 percent) are owned by Federal Government, including the National Park Service and the Army Corps of Engineers. The remaining bridges (1.4 percent) are owned and maintained by the private sector or state commissions. In Virginia, bridges for railroad travel are owned and maintained by the railroad companies.[31]

The HRTPO has available a GIS shapefile of the location of elevated structures that provide roadway travel (e.g., bridges and overpasses). For some of these structures, HRTPO realized the land at bare earth (below the structure elevation) was being identified as the structure elevation and used aerial photography to correct this effect when reviewing inundation flood scenarios.[32] In addition, VDOT provides shapefiles of the spatial extent and location of bridges and culverts at or greater than 20 feet in length (some municipalities collect spatial information for the smaller culverts).[33]

Use. The region is reliant on bridges to move both people and goods. The cumulative Average Daily Traffic (ADT) for bridges in HR is close to 24 million, as shown in Table 10. Table 10 shows that 77 percent of the traffic in HR and 91 percent of the traffic in Norfolk crosses over Stringer/multi-beam or girder bridges.

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[30] HRTPO (2015b).
[31] Per communication with Rodolfo Maruri, P.E., Federal Highway Administration, Virginia Division. Richmond, VA.
[32] HRTPO (2016).
[33] Per communication with representatives from HRTPO and HRPDC.

Table 10. Average daily traffic by bridge type in HR and Norfolk (2015 NBI)

STRUCTURE TYPE	HAMPTON ROADS		NORFOLK	
	ADT OF BRIDGES	PERCENT OF CUMULATIVE ADT	ADT OF BRIDGES	PERCENT OF CUMULATIVE ADT
SLAB	720,170	3.01	47,800	0.62
STRINGER/MULTI-BEAM OR GIRDER	18,410,042	77.03	7,013,419	90.58
GIRDER AND FLOORBEAM SYSTEM	171,044	0.72	-	-
TEE BEAM	224,082	0.94	9,300	0.12
BOX BEAM OR GIRDERS - MULTIPLE	645,445	2.70	163,550	2.11
BOX BEAM OR GIRDERS - SINGLE OR SPREAD	9,943	0.04	-	-
FRAME (EXCEPT FRAME CULVERTS)	72,391	0.30	-	-
TRUSS - DECK	100	0.00	-	-
TRUSS - THRU	3,759	0.02	-	-
ARCH - DECK	139,542	0.58	-	-
ARCH - THRU	7,817	0.03	-	-
MOVABLE - LIFT	57,251	0.24	-	-
MOVABLE - BASCULE	238,177	1.00	94,136	1.22
MOVABLE - SWING	70,619	0.30	-	-
CULVERT (INCLUDES FRAME CULVERTS)	3,120,808	13.06	414,546	5.35
OTHER	8,000	0.03	-	-
TOTAL	**23,899,190**		**7,742,751**	

In HR, the 2030 forecast suggest about a doubling of traffic in the HR compared to today (see

Table 11). Comparatively, Norfolk accounts for nearly one third of the vehicles, with an ADT of almost 8 million, including about 400,000 trucks (see Table 12). ADT in Norfolk is expected to more than double by 2030, to about 19 million vehicles.

Table 11. Present and future use of HR Bridges (Source: 2015 NBI)

FUNCTIONAL CLASSIFICATION	NUMBER OF HR BRIDGES	TOTAL LENGTH OF HR BRIDGES (METERS)	AVERAGE DAILY TRAFFIC (NUMBER OF VEHICLES)	2030 FORCAST OF AVERAGE DAILY TRAFFIC (NUMBER OF VEHICLES)	AVERAGE DAILY TRUCK TRAFFIC (NUMBER OF VEHICLES)
PRINCIPAL ARTERIAL - INTERSTATE	3,561	56,291	15,413,840	31,803,733	383,627
PRINCIPAL ARTERIAL - OTHER FREEWAYS OR EXPRESSWAYS	1,074	15,343	1,897,667	2,994,750	143,037
OTHER PRINCIPAL ARTERIAL	1,708	24,534	3,017,999	5,841,851	221,485
MINOR ARTERIAL	2,654	16,604	2,515,869	4,657,286	163,115
COLLECTOR	2,280	9,752	708,229	1,200,296	33,620
LOCAL	3,609	6,844	345,586	550,811	11,550
TOTAL	**14,886**	**129,368**	**23,899,190**	**47,048,727**	**956,434**

Table 12. Present and future use of Norfolk Bridges (Source: 2015 NBI)

FUNCTIONAL CLASSIFICATION	NUMBER OF NORFOLK BRIDGES	TOTAL LENGTH OF NORFOLK BRIDGES (METERS)	AVERAGE DAILY TRAFFIC, (NUMBER OF VEHICLES)	2030 FORECAST OF AVERAGE DAILY TRAFFIC (NUMBER OF VEHICLES)	AVERAGE DAILY TRUCK TRAFFIC (NUMBER OF VEHICLES)
PRINCIPAL ARTERIAL – INTERSTATE	135	17,383	6,538,987	16,858,663	330,365
PRINCIPAL ARTERIAL - OTHER FREEWAYS OR EXPRESSWAYS	2	202	27,090	42,500	984
OTHER PRINCIPAL ARTERIAL	32	5,073	935,164	1,570,500	52,135
MINOR ARTERIAL	12	2,203	155,348	244,500	8,081
COLLECTOR	6	364	58,390	72,500	5,125
LOCAL	3	48	7,276	9,425	1,110
GRAND TOTAL	**190**	**25,272**	**7,722,255**	**18,798,088**	**397,800**

Condition. Bridges in HR are aging with about 10 percent of the bridge inventory built prior to 1950, as are many other bridges in the nation.[34] The average bridge age in HR is 37 years (as of 2012), slightly lower than comparable metro areas.[35] Two metrics have been used in the past to quantify bridge condition: structural deficiency and scour rating. Recently, with the 2012 law Moving Ahead for Progress in the 21st Century (MAP-21), bridge performance measures were adopted that include deck condition, superstructure, substructure, and culverts.[36] This section considers all of these metrics in summarizing bridge condition.[37]

Structural deficiency. Standard engineering criteria for bridge "deficiency" consist of ratings for "structural deficiency" and "functional obsolescence." Bridges are labeled as structurally deficient when one or more major component is deteriorating (see Figure 5 for identification of deficient bridges).[38] A functionally obsolete bridge is a bridge that does not meet current design standards (i.e., it is not an indicator of condition). Such labels do not necessarily mean the bridge is unsafe but may require operational restrictions. According to the HRTPO Regional Bridge Study, adding up the two classifications, a total of 456 bridges in HR (37 percent) are classified as "deficient," making HR the third highest nationwide in its size class in this category.[39] Table 13 compares the HR bridge condition rating with the results of a recent GAO report stating that nearly a quarter of the Nation's bridges are deficient (10 percent as structurally deficient; and 14 percent as functionally obsolete).[40] The table underscores the fact that while 37 percent of HR's 1,223 bridges are classified as deficient, only 6.3 percent (77 bridges in HR) are classified as structurally deficient. Comparing the nation's ratio of 10 percent with the 6.3 percent rate of structurally deficient bridges in HR shows that condition of bridges in HR does not indicate above-average structural deficiencies.

Table 13. Highway bridge condition ratings in HR (Sources: GAO (2015); HRTPO (2012b))

CONDITION CATEGORY	COUNT OF HR BRIDGES	% OF HR BRIDGES	% OF BRIDGES NATIONALLY
FUNCTIONALLY OBSOLETE	379	31%	14%
STRUCTURALLY DEFICIENT	77	6.3%	10%
TOTAL FUNCTIONAL AND STRUCTURAL DEFICIENCY	**456**	**37%**	**24%**

[34] HRTPO (2012b).
[35] HRTPO (2012b).
[36] FHWA (2016a).
[37] In addition, see VDOT's Supplement to the AASHTO Manual for Bridge Element Inspection (2016): http://www.virginiadot.org/business/resources/bridge/VDOT_Suppl_to_the_AASHTO_Manual_for_Bridge_Element_Insp_2016.pdf.
[38] Appendix D describes the standards for bridge condition classification.
[39] According to the HRTPO report, HR is the third highest of comparable 35 metropolitan areas in percentage of deficient bridges (after Providence and Pittsburgh) in its size class. HRTPO (2012b).
[40] U. S. Government Accountability Office (GAO) (2015).

The National Bridge Inventory (NBI) data in the National Transportation Atlas Database show that 3 of 190 Norfolk bridges (1.6 percent) are structurally deficient.

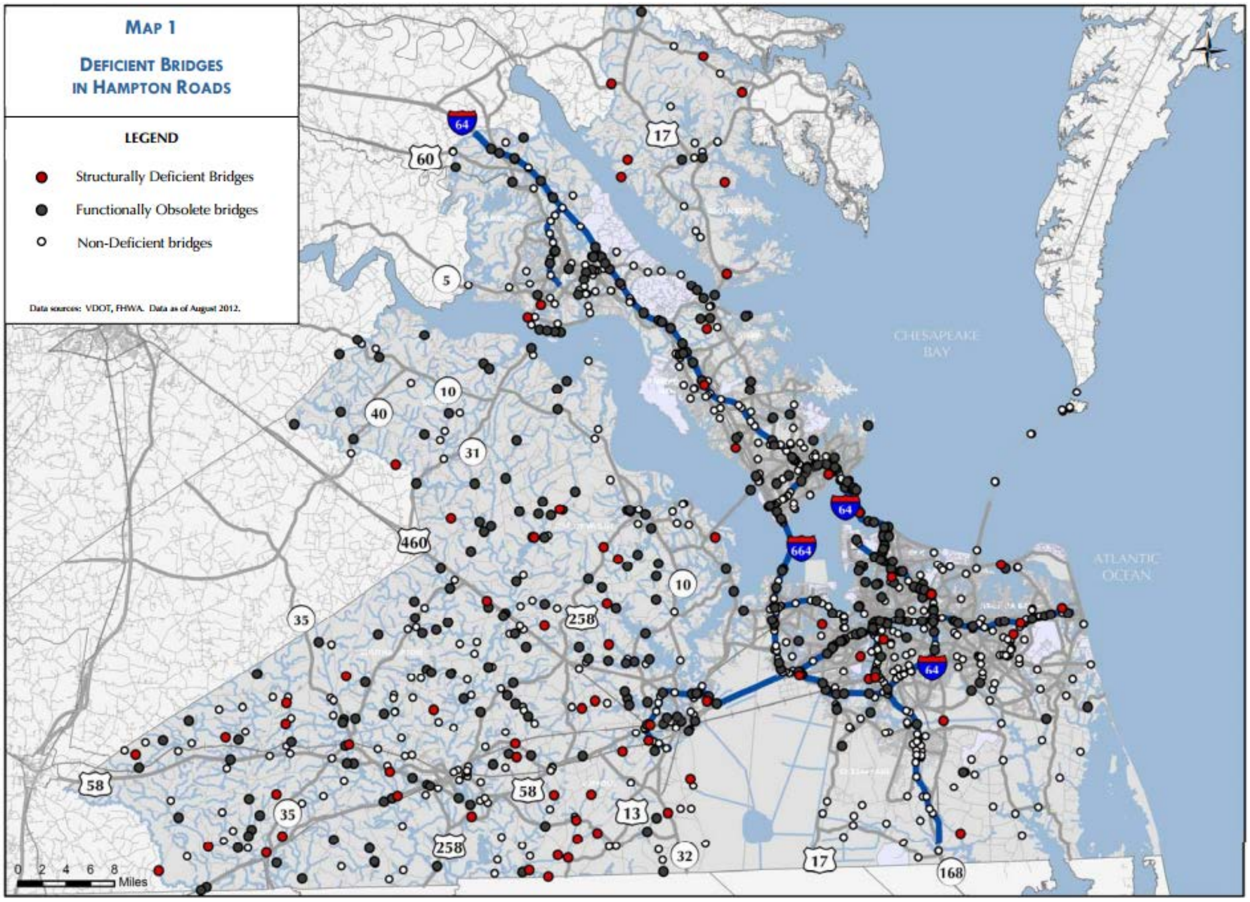

Figure 5. Deficient HR bridges (Source: HRTPO (2012b))

Bridge Scour. For bridges built over water that have underwater substructures, there is a code for Scour Critical Bridges that rates both bridge condition and risk of scour.[41] The Hazards United States – Multi Hazard (HAZUS-MH) bridge deficiency data are based on the Scour Critical Bridges codes from the NBI. The codes roughly describe the condition of the bridge and the risk of the bridge. Of the 190 bridges in Norfolk, 141 bridges are given a scour rating that indicates the bridge is not located over water. All of the remaining bridges that are over water in Norfolk are in acceptable condition.[42]

[41] Bridge scour is the erosive action of moving water carrying away sediment around the bridge pier or abutment, comprising bridge integrity.

[42] Bridge scour codes of 0, 1, 2, 3, 6, U, or T suggest some level of concern regarding scour. Bridge scour codes of 5, 8, N, and 0 are not of concern. In Hampton Roads, bridges have a scour code of 5, 8, or N. Appendix D contains the complete list of all the NBI Scour Critical Bridges codes.

MAP-21 Performance Measures. MAP-21 performance measures require ratings of the deck, superstructure, and substructure condition for bridges (see Figure 6), and conditions for culverts are also rated. The ratings are on a scale from 0 to 9, where 0 is a bridge with a deck in failure condition and 9 is a bridge with a deck in excellent condition.[43] The majority of bridges scored at least a 5 in deck, superstructure, and substructure condition (see Table 14). Culvert condition was largely not applicable or in fair/good condition. The overall bridge condition suggests HR bridges are in fair/good condition.

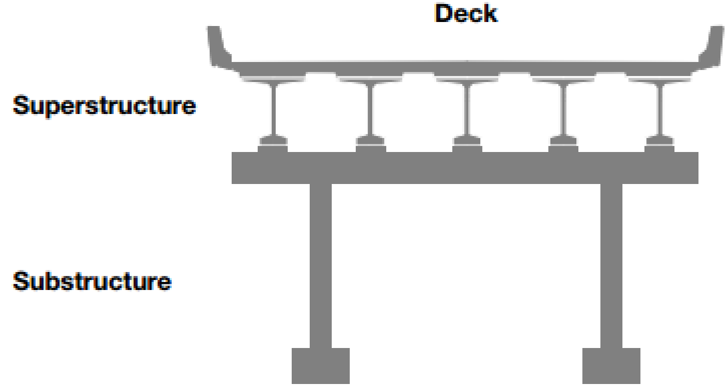

Figure 6. Anatomy of a bridge (WSDOT (2015))

Table 14. MAP-21 Performance measures for HR bridges (Source: 2015 NBI)

CONDITION	CULVERT		DECK		SUPERSTRUCTURE		SUBSTRUCTURE		BRIDGE CONDITION*	
	# of Culverts	**% of Culverts**	**# of Bridges**	**% of Bridges**	**# of Bridges**	**% of Bridges**	**# of Bridges**	**% of Bridges**	**# of Bridges**	**% of Bridges**
GOOD (7, 8, 9)	81	6.67	450	37.07	436	35.91	381	31.38	322	26.52
FAIR (4, 5, 6)	112	9.23	562	46.29	580	47.78	640	52.72	886	72.98
POOR (1, 2, 3)	-	-	2	0.16	5	0.41	-	-	6	0.49
NOT APPLICABLE	1021	84.10	200	16.47	193	15.90	193	15.90	-	-
TOTAL	**1214**		**1214**		**1214**		**1214**		**1214**	

*****_A bridge is rated in good conditions if all 3 bridge elements are rated at good; in fair condition if the lowest element is between 4 to 6; in poor condition if any element if below a 4._

[43] See Appendix D for a complete description of each of the codes for deck condition.

Bridges in Norfolk are rated at least in fair condition specifically for deck and substructure conditions (see Table 15).

Table 15. MAP-21 Performance measures for Norfolk bridges (Source: 2015 NBI)

CONDITION	CULVERT		DECK		SUPERSTRUCTURE		SUBSTRUCTURE		BRIDGE CONDITION*	
	# of Culverts	% of Culverts	# of Bridges	% of Bridges	# of Bridges	% of Bridges	# of Bridges	% of Bridges	# of Bridges	% of Bridges
GOOD (7, 8, 9)	4	2.11	65	34.21	57	30.00	50	26.32	28	14.74
FAIR (4, 5, 6)	7	3.68	114	60.00	122	64.21	129	67.89	162	85.26
POOR (1, 2, 3)	-	-	-	-	-	-	-	-	-	-
NOT APPLICABLE	179	94.21	11	5.79	11	5.79	11	5.79	-	-
TOTAL	**190**		**190**		**190**		**190**		**190**	

**A bridge is rated in good conditions if all 3 bridge elements are rated at good; in fair condition if the lowest element is between 4 to 6; in poor condition if any element if below a 4.*

Flooding Sensitivities

Bridges/tunnels. As flooding is projected to increase in HR, the following historic flood issues for bridges/tunnels offer helpful insight:

- The elevation and structural integrity of the approach to a bridge tends to represent a majority of closure risk (many bridges are sufficiently elevated above flood waters).
- Bridge-tunnels to the Virginia Peninsula historically experience flooding and closures.

Source: Sandia National Laboratories (2011).

Culverts. Design standards can provide some indication of possible sensitivities to climate-related stressors. For VA roadways, drawing from the Virginia Department of Transportation (VDOT) Drainage Manual, culverts are hydraulically designed at a minimum to operate under specific flood conditions to ensure maintenance of traffic flow and convenience of the highway user (see Table below). However, the design should allow for greater floods if there is the potential for adjacent property damage, loss of human life, or heavy financial loss. In addition, if the roadway is/will be located in the National Flood Insurance Program's (NFIP) 100-year floodplain, then the culvert must be part of a designed system that allows for the 100-year flood without raising the water surface elevation more than 1 foot. This is relevant when considering whether the magnitude of flood frequencies (annual risk) is going to change under a future climate and hence, suggest alternative adaptation options for managing flows.

Design standards for culverts in the Commonwealth of Virginia

Roadway	Flood Frequency (Annual Risk)
Interstate	50-year (2%)
Primary & Arterial	25-year (4%)
Secondary	10-year (10%)

Source: VDOT (2002).

Valuation. VDOT recommends using $75 (FY2000) as the average cost to construct one square foot of bridge.[44] To value the existing bridge, VDOT recommends the following methodology: (1) identify the year of the bridge; (2) calculate the square footage of the bridge; (3) multiply the square footage of the bridge by the cost to construct 1 square foot of bridge ($75/ft^2); (4) apply a deflation factor by year using the Consumer Price Index. For depreciation, VDOT suggests bridges have a useful life of 50 years and to apply a straight line depreciation method to estimate value. VDOT also has formulas for the cost of each foot of bridge elevation.[45] VDOT also recommends using the cost factor $100/ft^2 (FY2000) to estimate the average costs of building a culvert. The methodologies for estimating the costs for building a culvert based on today's dollars and to value existing culverts follows that detailed here for roads. For depreciation, VDOT suggests culverts have a useful life of 50 years.

[44] VDOT (2015a).
[45] Per communication with John Mazur at FHWA.

HAZUS-MH database provides another source of bridge valuation, representing replacement costs. A drawback of using HAZUS-MH is that it is based on information collected in 2001. For example, in Norfolk, the total valuation of $591.2M for the 190 highway bridges suggests an average cost of $3.1M to rebuild each highway bridge. Many DOT experts have commented on the low valuation of the regional bridge assets in the HAZUS-MH database. The value is also low because not all bridges in the dataset had valuations. This report recognizes this downward bias. This information can be accessed and analyzed for other regions within HR.

Valuation of rail bridges in HR, as documented in HAZUS-MH is even lower in value than what the experts view as reasonable. For example, Table 16 shows the HAZUS-MH valuation of the five rail bridges in Norfolk, along with the year built and their valuation, but no condition ranking. It shows a reported valuation of just $321,000 for the five railroad bridges (presumably all owned privately by the railroads), suggesting an average cost of $64,200 to rebuild a single bridge should it fail. The inconsistent figures for HAZUS-MH valuation of the unit costs for highway- and rail-bridge stock, and the overall down-side bias of the database's highway asset valuation, suggest that the validity of the underlying data needs to be verified.

Table 16. Railway Bridges in Norfolk (Sources: HAZUS-MH; 2001 NBI)

NAME OF BRIDGE	YEAR BUILT	HAZUS-MH VALUATION
COLLY AVE U NS RA	1972	$67,000
N&W RAILWAY	1952	$64,000
NS RAILWAY	1940	$53,000
TDWTR DR U NS RAI	1956	$64,000
VA BEACH BLVD U NS	1959	$73,000
GRAND TOTAL		**$321,000**

Regardless of accuracy of the valuation of the bridges, bridges are particularly costly to build and maintain. Funding has not kept up with bridge maintenance needs.[46] This is concerning because it is more cost effective to keep bridges in good condition than to repair bridges once they are in poor condition. The FHWA Bridge Preservation Guide states "[p]reservation activities often cost much less than major reconstruction or replacement activities."[47] Bridge length is a key factor in the engineering complexity and rebuilding costs. The 1,223 bridges in HR are particularly long: in total they span 565,000 feet, or an average of 460 feet for each bridge.[48] Given the high costs of bridge maintenance, the assessment of the condition of HR bridges as part of the region's climate change adaptation planning process plays a prominent role.

Movable Bridges. There are three main types of movable bridges: lift, bascule, and swing. Lift bridges raise the deck straight up above the waterway to allow boats to pass through. Bascule bridges rotate portions of

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[46] FHWA (2011a).
[47] FHWA (2011a).,
[48] According to HRTPO (2012b): Placed end-to-end, they span over 107 miles in total. The total deck area of HR bridges is 28,227,000 square feet. This ranks HR 8th highest among 35 comparable metropolitan areas (after New Orleans, St. Louis, Kansas City, Austin, San Antonio, Baltimore, and Pittsburgh).

the deck vertically with a counterweight. Swing bridges rotate a portion of the deck horizontally 90 degrees so boats can pass on either side.

Though non-movable bridges represent by far the greatest percentage of daily traffic, movable bridges are important to the region and can provide alternative routes (see Table 17). While the twelve movable bridges in HR make up slightly less than 1 percent of bridges in HR, they account for over 1.5 percent of average daily bridge traffic in the region, servicing some 366,000 vehicles every day. Movable bridges allow traffic to move both over and through waterways while avoiding high construction costs that come with building a stationary bridge high enough to allow for waterway traffic. However, they are more expensive to operate, as they require machinery, staff, and extensive maintenance.

Table 17. Average number, percent, and average daily traffic (hour) by bridge type (move-able versus non-movable) in HR and Norfolk (Source: 2015 NBI)

STRUCTURE TYPE	# OF BRIDGES HR	% BRIDGES HR	# OF BRIDGES NORFOLK	% OF BRIDGES NORFOLK
MOVABLE-LIFT	3	0.25	0	0.00
MOVABLE-BASCULE	6	0.49	2	1.05
MOVABLE-SWING	3	0.25	0	0.00
NON-MOVABLE	1,202	99.01	188	98.95
TOTAL	**1,214**		**190**	
STRUCTURE TYPE	**ADT of Bridges HR**	**% ADT HR**	**ADT of Bridges Norfolk**	**% ADT Norfolk**
MOVABLE-LIFT	57,251.00	0.24	-	-
MOVABLE-BASCULE	238,177.00	1.00	94,136.00	1.22
MOVABLE-SWING	70,619.00	0.30	-	-
NON-MOVABLE	23,533,143.00	98.47	7,648,615.00	98.78
TOTAL	**23,899,190.00**		**7,742,751.00**	

Five of the movable bridges account for more than 75 percent of average daily traffic on movable bridges in HR. They are the Berkley Bridge, the High Rise Bridge, the James River Bridge, the Gilmerton Bridge, and the Coleman Bridge. Three of these bridges (Berkley, High Rise, and Gilmerton) cross the Elizabeth River and serve as important alternate routes to the Downtown and Midtown Tunnels. The James River Bridge is used as an alternate to the HRBT and MMBT when they are congested.[49] These movable bridges are not scour critical, and their deck conditions ranges from fair to good (see Table 18).

[49] VDOT (2016).

Table 18. Average daily traffic (number of vehicles), scour condition, and deck condition for critical movable bridges in HR (Sources: per communication with HRTPO/HRPDC; 2015 NBI)

BRIDGE	ADT OF BRIDGES (HR)	SCOUR CODE	DECK CONDITION
GILMERTON	31,000	5	7
JAMES RIVER	28,000	5	5
BERKLEY EAST BOUND	49,000	5	6
BERKLEY WEST BOUND	49,000	5	6
HIGH RISE	89,000	5	5
COLEMAN	32,000	8	6

A few questions of interest when comparing the costs of extreme weather impacts on movable bridges to non-movable bridges: Are movable bridges at greater risk to extreme weather events than non-movable bridges (e.g., can lines sag or the integrity of lines be comprised during heat events)? Do movable bridges incur greater costs when damaged by an extreme event and/or require longer repair time than non-movable bridges? Is there a greater economic consequence of damage to a movable bridges due to impact on both roadway and waterway traffic?

Tunnels

Ownership and Inventory. Like bridges, tunnels serve a critical role in connecting the HR region, enabling enhanced mobility since the first tunnel opening in 1952. Figure 7 shows the five major tunnel complexes that connect Hampton Roads, followed by a description of each asset in Table 19.

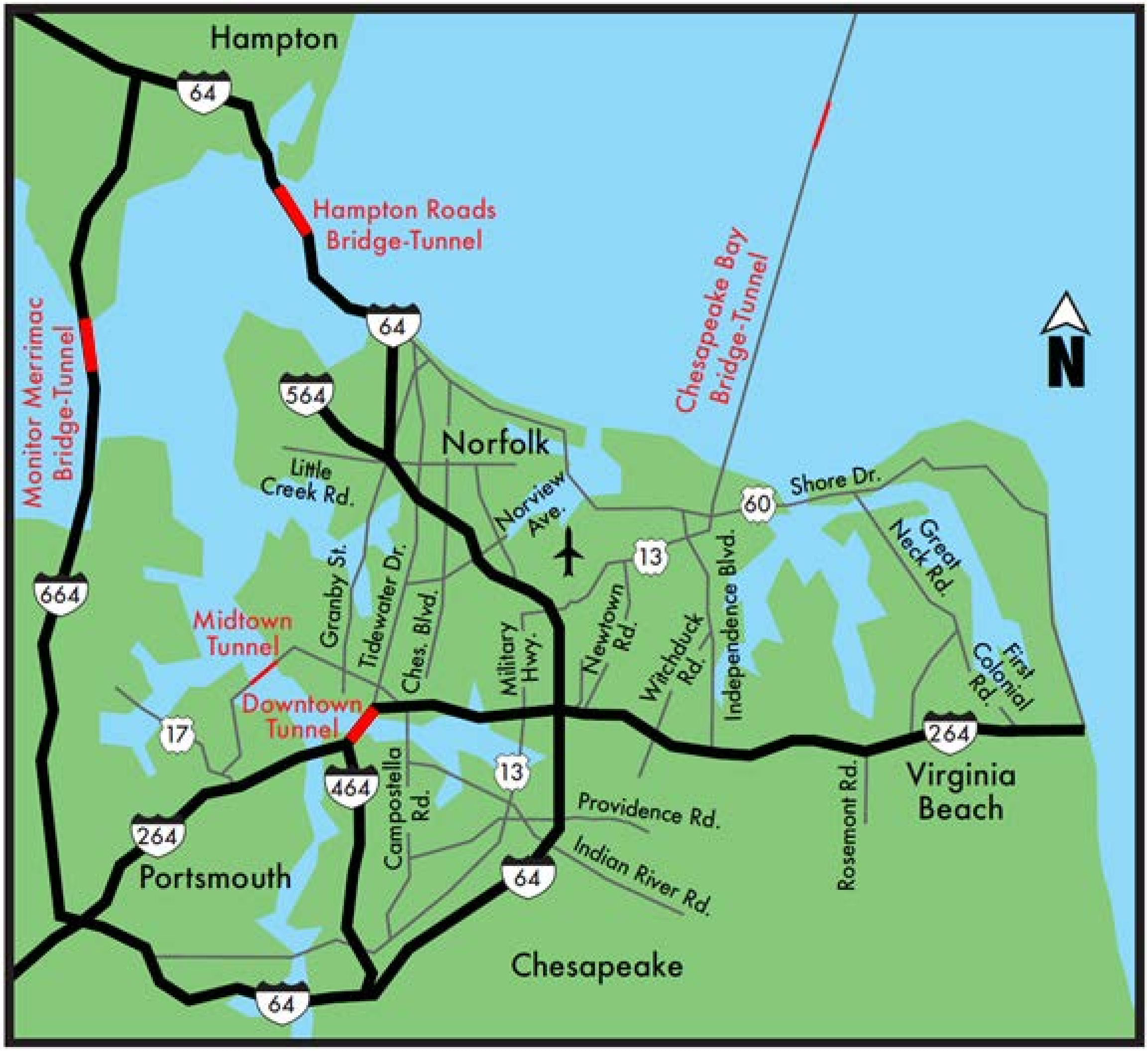

Figure 7. Tunnels connecting Hampton Roads. (Source: Old Dominion University annotated with tunnel locations)

Table 19. Description of the five major tunnel complexes in HR (Sources: VDOT (2016); per communication with HRTPO/HRPDC)

HAMPTON ROADS BRIDGE-TUNNEL / HRBT (I-64)

OPENED:	The first two-lane Hampton Roads Bridge-Tunnel (HRBT) opened in 1957; the second opened in 1976. Owned by VDOT.[50]
WATER CROSSING:	Spans Hampton Roads Harbor.
CONNECTS:	Connects Hampton and Newport News to Norfolk and Virginia Beach.
LENGTH:	3.5 miles
TRAFFIC VOLUME:	About 86,000 vehicles per day, more during the tourist season.[51] During heavy traffic, many motorists use the MMMBT on I-664 instead.

[50] Benefit from a VDOT continual maintenance and operations program; Per communication with VDOT.

[51] Traffic numbers for HRBT, MMMBT, Downtown, and Midtown tunnels are given in vehicles per month at VDOT's website, and were converted to per day values assuming a month has 30 days.

MONITOR-MERRIMAC MEMORIAL BRIDGE-TUNNEL / MMMBT (I-664)

OPENED:	The Monitor-Merrimac Memorial Bridge-Tunnel (MMMBT) opened in 1992 as a four-lane, dual-tunnel system. Owned by VDOT.[52]
WATER CROSSING:	Spans Hampton Roads Harbor.
CONNECTS:	Connects Newport News and Hampton to Suffolk and Chesapeake.
LENGTH:	4.6 miles
TRAFFIC VOLUME:	MMMBT serves as a less-congested alternative to the HRBT, normally carrying half the daily vehicular traffic volume of the HRBT (e.g., 62,000 vehicles per day).

DOWNTOWN TUNNEL (I-264)

OPENED:	The first two-lane Downtown Tunnel opened in 1952; the second opened in 1987. Leased to and operated by ERC.
WATER CROSSING:	Spans the Elizabeth River.
CONNECTS:	Links Norfolk and Portsmouth.
LENGTH:	0.65 miles
TRAFFIC VOLUME:	The Downtown Tunnel carries over 100,000 vehicles per day.

MIDTOWN TUNNEL (ROUTE 58)

OPENED:	The Midtown Tunnel opened in 1962 as the second tunnel connecting Norfolk and Portsmouth (built after the Downtown Tunnel). Leased to and operated by ERC. The second two-lane tunnel opened in 2016.
WATER CROSSING:	Spans the Elizabeth River.
CONNECTS:	Links Norfolk and Portsmouth.
LENGTH:	0.8 miles
TRAFFIC VOLUME:	The Midtown Tunnel carries over 33,000 vehicles per day.

CHESAPEAKE BAY BRIDGE-TUNNEL / CBBT (ROUTE 13)

OPENED:	The first two-lane Chesapeake Bay Bridge-Tunnel (CBBT) opened in 1964; the second parallel crossing opened in 1999. Privately owned.
WATER CROSSING:	Spans the mouth of Chesapeake Bay.
CONNECTS:	Connects Virginia Beach to Cape Charles in Northampton County.
LENGTH:	17.6 miles; the CBBT is the world's largest bridge-tunnel complex.
TRAFFIC VOLUME:	The CBBT had 3,796,973 vehicles in 2015, which is more than 10,000 per day.[53]

Use. The five major tunnels experience traffic volume from 10,000 to over 100,000 vehicles per day (see Table 19). With respect to tunnel capacity and congestion, four of the five major tunnel complexes in Hampton Roads were considered "choke points" (Figure 8). VDOT indicates that there have been recent improvements to the Midtown Tunnel and in response to the Elizabeth River Crossing Project. Improvements to the Midtown Tunnel occurred in response to flooding during Hurricane Isabel, including the reconstruction of the tunnel approach on the Norfolk-side from three feet to eight feet elevation to reduce future flooding of the tunnel

[53] Chesapeake Bay Bridge and Tunnel Commission (2016).

[53] Chesapeake Bay Bridge and Tunnel Commission (2016).

and account for future SLR.[54] Another tunnel will be added that will increase the number of lanes from 2 to 4. The expansion is expected to save the average user 30 minutes a day.[55] VDOT, since the 1990s, has also been examining options for adding a third Hampton Roads crossing for numerous reasons: to address congestion at the HRBT; provide transit access across the HR waterway; enhance evacuation capability; and increase port facilities access, among other objectives. Currently VDOT is re-evaluating options originally scoped in the *Hampton Roads Crossing Study* (2001), in cooperation with other federal/state authorities and the public. All of the design alternatives being considered involve the construction of new bridge/tunnel complexes, either adjacent to existing installations or in new locations.[56]

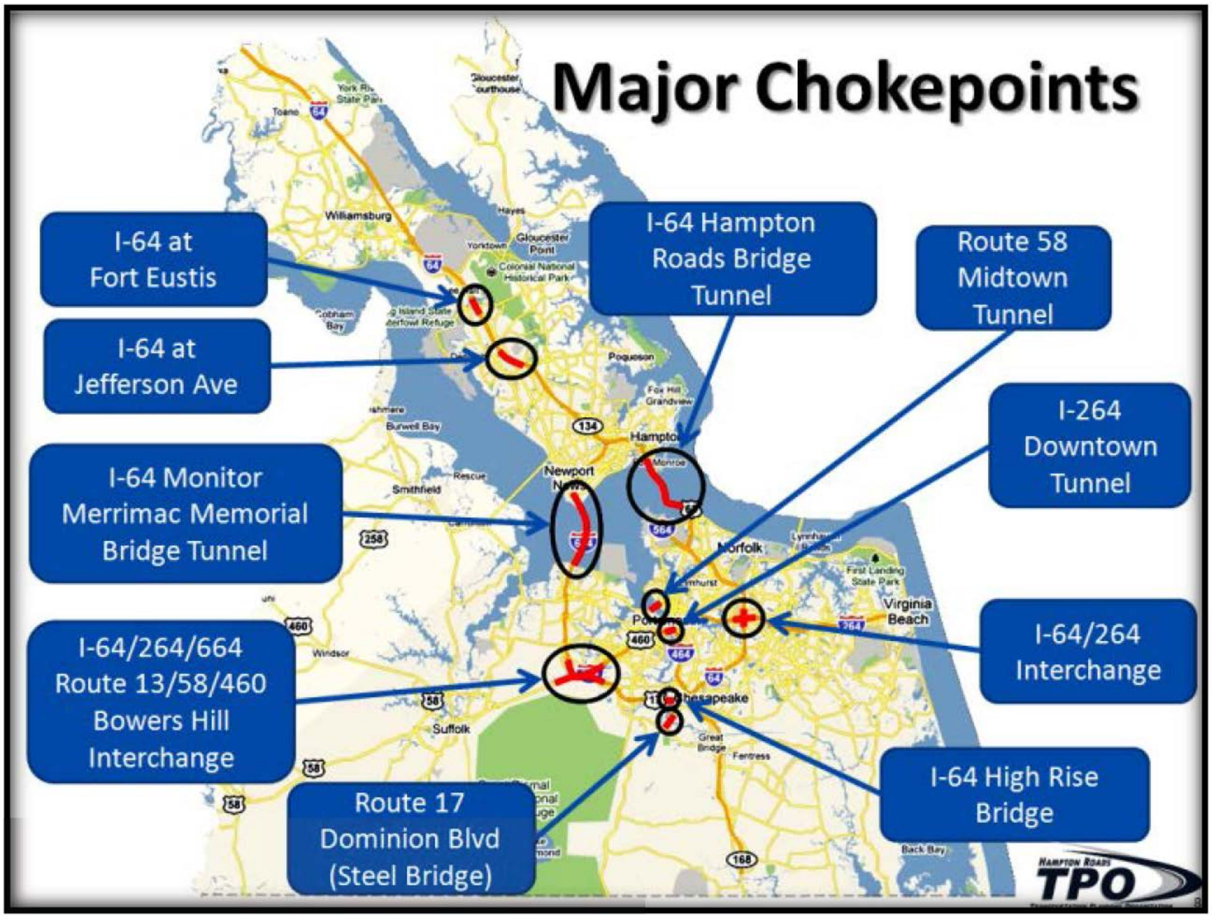

Figure 8. Major traffic chokepoints in Hampton Roads (Source: HRTPO)

[54] Per communication with John Mazur at FHWA.
[55] Elizabeth River Tunnels (2016a).
[56] VDOT (2001).

Condition. Unlike bridges, which have been overseen by the National Bridge Inspection Program (NBIP) for over 40 years, tunnels have not been subject to national inspection requirements or standards. In 2012 MAP-21 directed Federal Highway Administration (FHWA) to compile an inventory of the nation's tunnels and begin to develop a national database similar to the National Bridge Inventory (NBI). In addition to a new *National Tunnel Inventory (NTI)*, the law directed the establishment of new *National Tunnel Inspection Standards (NTIS),* to be modeled after the National Bridge Inspection Standards (NBIS) currently used to ensure the inspection of bridges throughout the country.[57] In 2015, final rulemaking for the NTIS was issued in addition to specifications for the NTI. However at the time of this report, complete national tunnel inventory data, including Federal information on tunnel health and condition, has not yet been released. Full data sets for the NTI are due to be submitted in the spring of 2018. The NTI will include a number of attributes that will be of interest to this report, including: average daily traffic, detour length, damage inspection, navigable waterway clearance, and tunnel or portal island protection. The NTI will also include condition data on various structures and systems in tunnels, such as liners, ventilation systems, lighting systems, and protective systems.

Hampton Roads tunnels are regularly inspected. Aside from obstructions caused by vehicular accidents, some common risks to tunnel operation include flooding (from weather events, groundwater infiltration, and pipe bursts), fire, pavement wear, and the compromised integrity of tunnel roof panels and other structural components.

The Midtown tunnel is currently undergoing an expansion that will include wider lanes and shoulders. This will allow emergency crews to clear broken or wrecked vehicles from the tunnel without a completely closing the tunnel.[58] The Downtown Tunnel is currently being rehabilitated. The rehabilitation includes tunnel fireproofing, a new ventilation system, LED lighting, tile and concrete repair, and updating signage.[59,60]

Bridge component characteristics of the three major HR tunnel/bridge complexes (HRBT, MMMBT, and CBBT) are captured in the NBI. Both the HRBT and the MMMBT have bridge segments that are classified as

[57] FHWA (2015).
[58] WAVY (2016).
[59] Elizabeth River Tunnels (2016b)..
[60] A project being considered is changing the high-rise draw bridge (I-64) to a fix span bridge with enough elevation to allow for ships underneath. The elevation is to account for 5 feet of SLR. Per communication with John Mazur FHWA.

functionally obsolete, and part of the HRBT is classified as structurally deficient. The CBBT, which is privately operated, is classified in-whole as non-deficient.[61]

> **Tunnel Sensitivity to Flooding**
>
> *To protect the integrity of the infrastructure, some tunnels physically close during extreme flooding using either gates or inflatable stoppers.*
>
> Source: Sandia National Laboratories (2011).

Valuation. VDOT suggests using an estimate of $20/ft^2 (FY2000) for constructing tunnels.[62] The methodology for converting this estimate to today's dollars and for estimating valuation of existing tunnels follows that described in the valuation section of roads.

This analysis found additional valuation information for tunnels considering costs of past projects. The original Chesapeake Bay Bridge Tunnel cost $200 million to build in 1960.[63] The parallel crossing that opened in 1991 cost $197,185,777.[64] In 1957, the $44 million Hampton Roads Bridge Tunnel opened. A parallel crossing for the HRBT opened in 1976 at the cost of $95 million. The HRBT was rehabilitated (shoulders were widened, a new bridge deck was built) for $34.7 million in 1999.[65] The MMMBT, built in 1992, cost $400 million.[66]

[61] HRTPO (2012b).
[62] VDOT (2015a).
[63] Note: Dollar values have not been adjusted for inflation.
[64] Chesapeake Bay Bridge and Tunnel Commission (2014).
[65] Kozel (2007).
[66] Kozel (2004).

Railroads

Ownership and Inventory. According to the 2015 Railway Network from the National Transportation Atlas Database, there are approximately 532 miles of rail corridor and close to 600 miles of track in HR (see Table 20). Suffolk has the greatest number of rail infrastructure with 130 miles of rail, followed by Chesapeake with 76 miles.

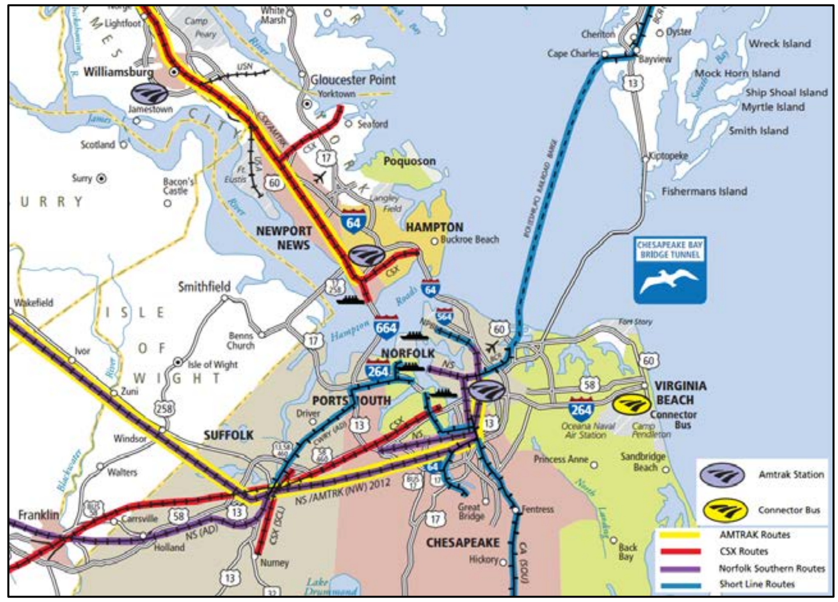

Figure 9. Hampton Roads rail lines (Source: VA Department of Rails and Public Transit (DRPT) (2012))

Table 20. Railway Network in HR (Source: NTAD)

CITY/COUNTY	MILES OF RAIL CORRIDOR	MILES OF TRACK	CITY/COUNTY	MILES OF RAIL CORRIDOR	MILES OF TRACK
GLOUCESTER COUNTY	-	-	HAMPTON	11.0	11.0
ISLE OF WIGHT COUNTU	30.8	40.0	NEWPORT NEWS	48.6	58.7
JAMES CITY COUNTY	18.2	26.5	NORFOLK	65.2	85.0
MATTHEWS COUNTY	-	-	POQUOSON	-	-
SOUTHAMPTON COUNTY	81.1	89.4	PORTSMOUTH	23.8	23.8
SURRY COUNTY	-	-	SUFFOLK	130.2	133.3
YORK COUNTY	12.0	14.4	VIRGINIA BEACH	35.0	35.0
CHESAPEAKE	75.7	87.3	WILLIAMSBURG	5.0	5.0
FRANKLIN	4.0	4.0			
TOTAL	**532.3**	**598.5**			

As shown by Table 21,

Table 21 CSX Transportation and Norfolk Southern are the two largest railroads owners in the Hampton Roads region. CSX owns 23% of rail corridors by mileage, and 24% of the track by mileage. Norfolk Southern owns 31% of the rail corridor and 35% of the track. A combination of other owners account for the remaining 45% of corridor and 41% of track. For location purposes, VDOT provides shapefiles of the spatial extent and location of rail assets in HR.

Table 21. Railroad ownership in HR (Source: NTAD)

OWNER	MILES OF RAIL CORRIDOR	% OF RAIL CORRIDOR	MILES OF TRACK	% OF TRACK
CSX TRANSPORTATION	124.6	23.41	145.8	24.36
NORFOLK SOUTHERN	166.4	31.26	208.6	34.85
OTHER	241.3	45.3	244.2	40.8
TOTAL	**532.3**	-	**598.5**	-

For the Norfolk area, there are 57 miles of rail corridor, and a total of 68 miles of track.[67] Table 22 shows the total length of the railway network. The Tide is a light-rail service with 7.4-miles of track in downtown Norfolk, as described in the Transit Section. Figure 10 illustrates the locations of rail lines in and around Norfolk.

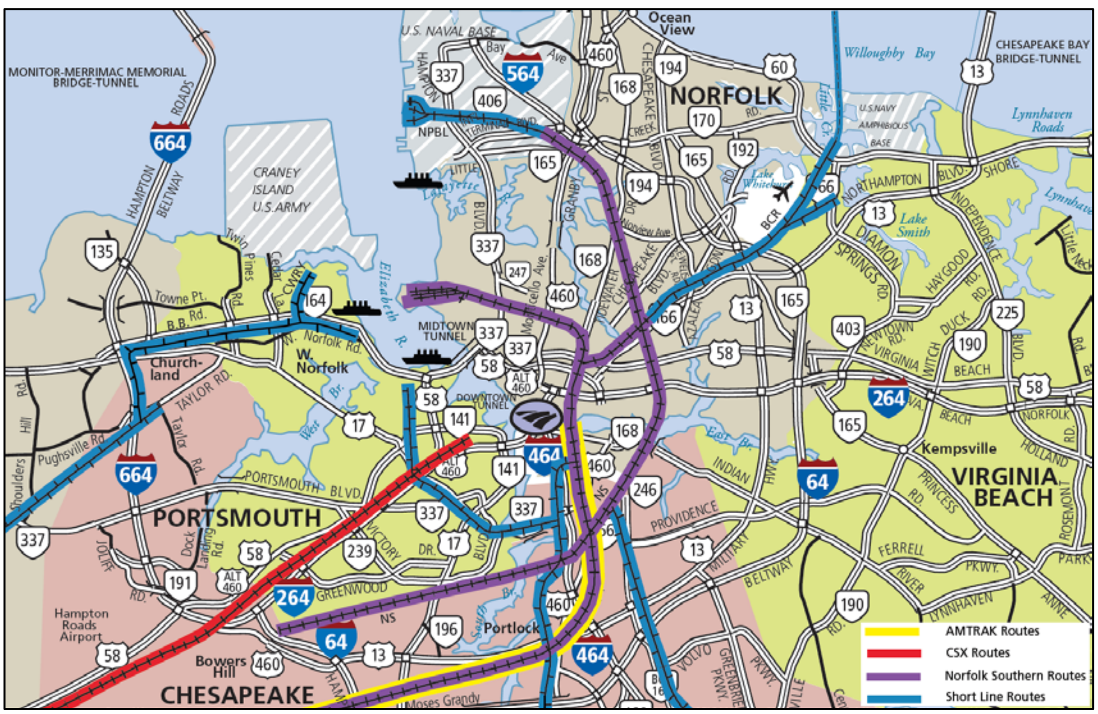

Figure 10. Hampton Roads rail lines; Southside Hampton Roads rail lines (Norfolk & vicinity) (Source: VA Department of Rails and Public Transit (DRPT) (2012))

67 National Transportation Atlas Database (2015) .

Table 22: Railway network in Norfolk (Sources: NTAD and Norfolk OpenGIS)[68]

RAIL NETWORK	MILES OF RAIL CORRIDOR	MILES OF TRACK
PASSENGER RAIL (AMTRAK)	1.0	2.0
LIGHT RAIL	7.4	14.8*
FREIGHT RAIL	56.8	68.2**

**Includes both eastbound and westbound tracks. **Includes freight rail sidings.*

Use. During FY 2015, there were a total of 160,292 AMTRAK boardings and alightings in HR, which is about 10 percent of the total for Virginia.[69] In 2015, AMTRAK recorded 115,440 boardings and alightings in Newport News, 61,625 boardings and alightings in Williamsburg, and 44,852 boardings and alightings in Norfolk.

Condition. This analysis did not uncover data/information regarding the condition of rails.

Valuation. Data on valuation of rail track assets in Norfolk, obtained from the HAZUS-MH database for 93.8 mile of rail, suggest a total direct replacement cost for the Norfolk rail network at $83,428,000, in nominal dollars (with no information on the date of the estimate).[70] The range of cost estimates per track type, per kilometer, is between $1.5M for a regular segment of railway track to $10M for railway tunnels.[71]

[68] Norfolk, City of, *Open GIS*, "Light Rail."http://data.orf.opendata.arcgis.com/datasets/54ed990ea6ba42a9b6940d5913692edf_0.
[69] AMTRAK (2015).
[70] Appendix D shows the HAZUS-MH cost estimates for specific components of the rail network.
[71] The HAZUS-MH database contains data on 93.8 miles of rail tracks for Norfolk, 8.8 miles greater than the total in the 2015 National Transportation Atlas Database (NTAD). One potential reason for the discrepancy is the fact that HAZUS-MH uses data from the 2001 version of NTAD, and perhaps reflects rail tracks that have since been removed from service. The HAZUS-MH helpdesk reports these estimates are dated, and no other information is available about more recent rail track costs.

Airports

Ownership and Inventory. Virginia has a total of nine primary commercial airports, as well as a number of military airports. Norfolk International Airport (ORF), a Federal Aviation Administration (FAA) National Plan of Integrated Airport Systems (NPIAS) classified as a small/non-hub airport with a significant military usage, is located in a densely populated area adjacent to the Chesapeake Bay (see Figure 11).[72] Norfolk International Airport is owned by the City of Norfolk with operations run by the Norfolk Airport Authority. Chambers Field (NAS) is owned and operated by the Navy.

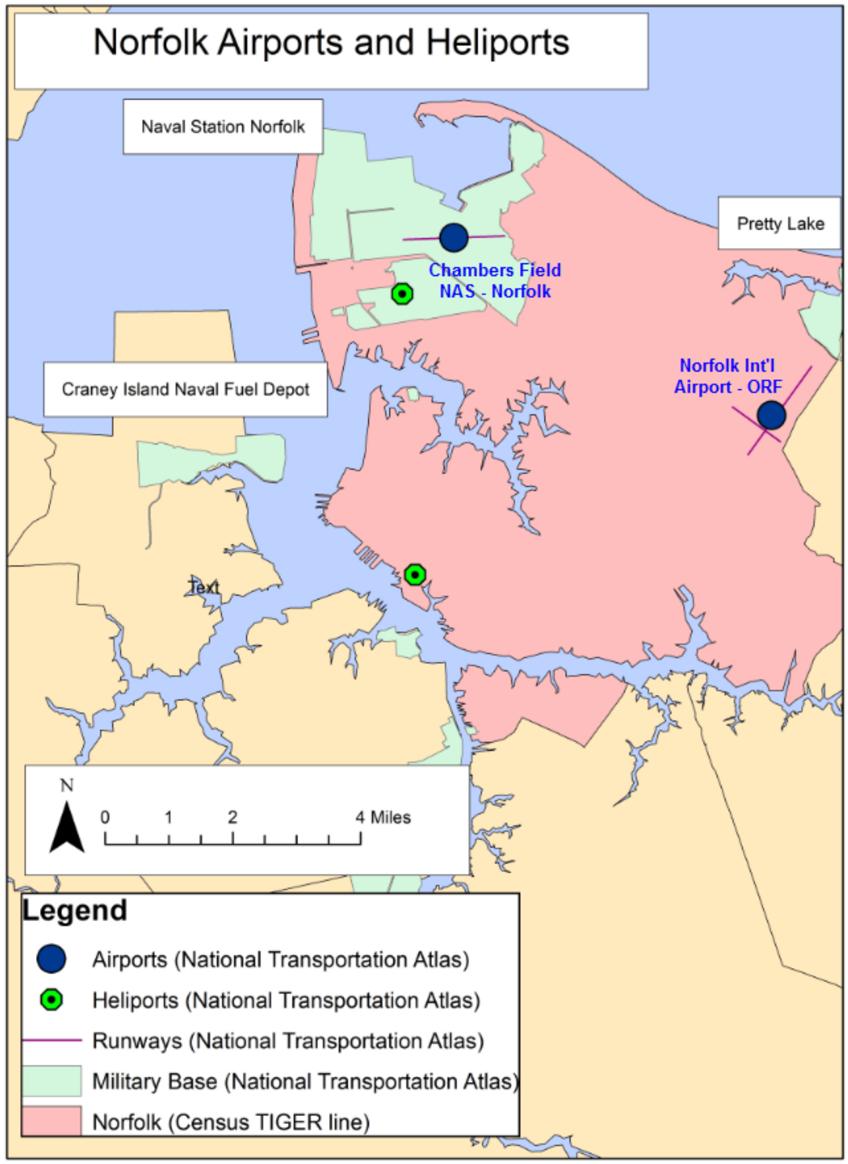

Figure 11. Norfolk Airports and Heliports (Source: NTAD)

Use. The nine primary commercial airports in the Commonwealth of Virginia experienced total enplanements of 24,480,117 in 2013.[73] For 2014, the FAA National Plan of Integrated Airport Systems (NPIAS) database indicates total enplanements of 24,467,633.[74] Airport traffic at Virginia's top four airports, with total enplanements of 23.6M, account for over 96 percent of total aviation traffic within the Commonwealth (see Table 23). Enplanements for ORF since 2004 have risen from 1.25 million in 2004 to a peak of 1.81 million in 2007, stabilizing round 1.6 million in 2013.[75] Usage data is not available for NAS because it is a military facility.

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[72] The remaining five smaller airports are Roanoke Regional (ROA), (310K); Newport News (PHF), (264K); Charlottesville (CHO), (231K); Lynchburg Regional (LYH), (78K); and Shenandoah Valley Regional (SHD), (20K).
[73] Old Dominion University (ODU) (2015).
[74] 2014 data may be obtained from the *National Plan of Integrated Airport Systems (NPIAS) Report.* FAA. See: http://www.faa.gov/airports/planning_capacity/npias/reports.
[75] See above reference for obtaining 2014 NPIAS data.

Table 23. Enplanements at Virginia's four busiest airports (Source: VA Chamber Foundation (2015))

AIRPORT	ENPLANEMENTS IN 2013 (MILLIONS)
WASHINGTON DULLES AIRPORT (IAD)	10.6
REAGAN NATIONAL INTERNATIONAL AIRPORT (DCA)	9.8
RICHMOND/HIGHLAND SPRINGS AIRPORT (RIC)	1.6
NORFOLK INTERNATIONAL AIRPORT (ORF)	**1.6**
TOTAL ENPLANEMENTS (IAD, DCA, RIC, ORF)	**23.6**
OTHER AIRPORTS	0.9
TOTAL VA ENPLANEMENTS	24.5

Operations are also significant measures on airport performance. FAA defines "Total Enplanement" as "revenue passenger boarding," while "Total Operations" refers to the number of take-offs and landings at that airport. Table 24 shows Total Operations for ORF, IAS, DCA and RIC for 2014 from the FAA Air Traffic Activity Data System (ATADS).

Table 24. ATADS-reported 2014 airport operations for ORF, IAS, DCA and RIC (Source: FAA ATADS)

FACILITY	ITERANT					LOCAL			TOTAL OPERATION
	Air Carrier	**Air Taxi**	**General Aviation**	**Military**	**Total**	**Civil**	**Military**	**Total**	
DCA	204,586	75,976	3,805	3,055	287,422	0	0	0	287,422
IAD	152,850	121,955	39,113	594	314,512	0	0	0	314,512
ORF	**26,126**	**25,483**	**18,182**	**1,010**	**70,801**	**3,905**	**141**	**4,046**	**74,847**
RIC	32,390	33,006	23,571	4,351	93,318	5,322	2,162	7,484	100,802
PHF	1,738	12,607	22,180	7,010	43,535	28,093	11,808	39,901	83,436

Condition. This analysis did not uncover data/information regarding the condition of airports.

Valuation. A study conducted in 2011 for the Virginia Department of Aviation on the economic performance of the nine Virginia commercial airports estimated the total economic impact of aviation for the commonwealth to be $20B. The report showed Norfolk's ORF to have total statewide economic impact of approximately $1B.[76]

This is similar to another study that estimated the ORF's total economic impact—direct, indirect, and induced impacts—at $1.36 billion.[77] The study noted that while the airport's direct contribution to the regional economy was relatively small, the indirect and induced impacts in terms of the multiplier effects of non-airport jobs and revenues with the supply chain have generated significant benefits for the entire HR region:

[76] Virginia Department of Aviation (2011)
[77] Norfolk Airport Authority (2007)

- *Direct economic impacts* accounted for roughly $136M (10 percent) of the economic impact, generated from passenger and cargo airline revenues, airport services and purchases;[78]

- *Indirect economic impacts* accounted for roughly $567M (42 percent) of the economic impact, generated by revenues and spending in supporting sectors not directly related to the airport;

- The *induced economic impacts* accounted for roughly $655M (48 percent) of the economic impact, revenues and incomes that are generated as the multiplier effect of the airport operations. The report indicated that these induced multiplier benefits of the airport are spread through the total regional economy, but primarily in Chesapeake, Portsmouth, Virginia Beach and Norfolk.

Sea Ports and Waterways

Ownership and Inventory. Port of Virginia (POV) is the gateway for waterborne cargo flowing through the region. Within this region there are state-owned and privately-owned terminals. State-owned or operated facilities are managed by the Virginia Port Authority, which owns or leases the region's four container cargo facilities: Norfolk International Terminal (NIT); Virginia International Gateway Terminals (VIG) and Portsmouth Marine Terminal (PMT) in Portsmouth, and Richmond Marine Terminal (RMT) in Richmond; and Newport News Marine Terminal (NNMT), a breakbulk and roll-on/roll-off terminal in Newport News.. The Virginia Port Authority created the Virginia International Terminals, a private non-profit organization, which is the operating arm that oversees daily operations.[79] In addition to these terminals, there are a number of privately owned marine terminals critical to the region's cargo movement.

These ports are responsible for the movement of a variety of goods. About 65 percent of deep draft ships call at the container terminals, 15 percent carry export coal moved through the coal terminals, and 20 percent call other private bulk terminals.[80] Bulk commodities may include the export of soy, grains, and wood chip products and the import of petroleum and fertilizers, among other goods.[81]

Use. In 2014, POV ranked as the 5th largest port in the US by container volume,[82] with peak season from August to November (which overlaps with hurricane season).[83]

NIT, VIG, and NNMT form the port's hub (see Figure 12). Deep channels, frequent weekly ocean-going vessel schedules, an efficient set of inland intermodal container transportation alternatives, and beneficial Foreign Trade Zone (FTZ) options combine to boost the HR port business. The Economic Impacts of the Virginia

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[78] It should be emphasized that the ORF study was conducted in 2004, thus reflecting the lingering slowdown in air travel in the aftermath of the September 11, 2001 events.
[79] Old Dominium University (2015). Virginia International Terminals was established as a private nonprofit to allow for negotiations of contracts with unionized labor.
[80] Per interview with David White at the Virginia Maritime Association (8/8/2016).
[81] Per interview with David White at the Virginia Maritime Association (8/8/2016).
[82] Virginia Maritime Association (2016b).
[83] Per interview with David White at the Virginia Maritime Association (8/8/2016).

Maritime Industry report shows that the Virginia ports handled 78.9 million tons of domestic and foreign cargo in FY 2013, with an estimated value of $75.4 billion.[84] Below is a snapshot of the POV cargo movement profile:[85]

- *The Norfolk International Terminal (NIT*) container port operates on 378 of its total 567 acres with 14 Super Post Panamax ship-to-shore cranes with capacity to move 820,000 containers, equivalent to 1,426,800 Twenty-foot Equivalent Units (TEUs).

- *Virginia International Gateway Terminal (VIG)* in Portsmouth is privately owned, but operated by POV. It is a highly automated container terminal operating on 231 acres of a 576-acre tract. VIG has eight Super Post Panamax cranes with capacity to handle 650,000 containers (1,131,000 TEUs).

- *Newport News Marine Terminal (NNMT),* located on 165 acres north of the James River is POV's main breakbulk and roll-on/roll-off container facility.

- *Portsmouth Marine Terminal (PMT),* located on 287 acres along the Elizabeth River, did not have any operations in 2011, with studies underway for alternative future uses of PMT.

Both NIT and VIG have 50-foot-deep channels, making them well positioned to accommodate super containerships that are coming on line with the expansion of the Panama Canal. With a combined capacity of 2,557,800 TEU, the two ports in 2013 handled 2,165,435 TEU, or 85 percent of their total capacity. In 2014, the Mason School study reports a 6.5 percent growth for the ports, with a record container activity of 2,305,911 TEU, equal to 90 percent of the combined NIT and VIG container capacity. POV does not handle bulk coal cargo; all bulk coal moves are handled by private HR terminals.[86]

[84] Virginia Maritime Association (2016a).
[85] College of William & Mary (2014).
[86] HR coal ports include: Lambert's Point/Pier 6, in Norfolk (owned by Norfolk Southern); Pier IX, in Newport News (owned and operated by Kinder Morgan), and; Dominion Terminal Associates, in Newport News (owned by Arch Coal, Peabody Energy and Alpha Natural Resources). Source: Platts (2016).

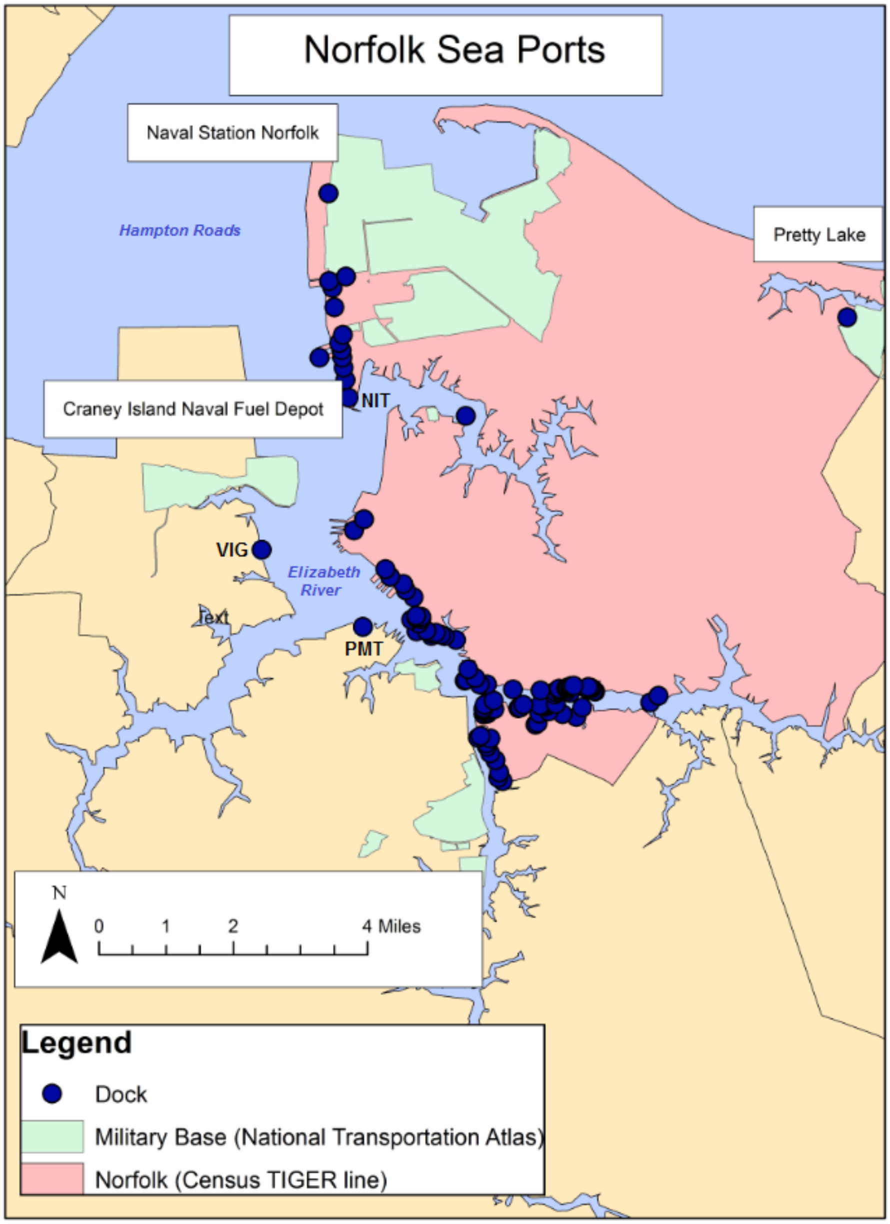

Figure 12. Norfolk Seaports (Source: National Transportation Atlas Database (NTAD))

A key measure of port activity is the volume of cargo containers moved by export or import vessels in domestic and international trade. Trucks carry 63 percent of the volume (778,316 TEUs), with the remaining balance carried by rail (410,947 TEUs, or 33 percent) and barge (53,514 TEUs, or 4 percent).[87] In the past few years, data on record growth rates in both POV tonnage and TEU movements suggest that POV has been one of the fastest-growing ports on the East Coast. In calendar year 2012, cargo tonnage grew to 17.53M tons (a

[87] Hampton Roads Partnership (2013).

12.2 percent tonnage growth); while TEU volume grew 10 percent in FY 2013, reaching a record volume of 2,165,435 TEUs. [88] Figure 13 shows the TEU container volumes by mode for the 2012-2013 time period.

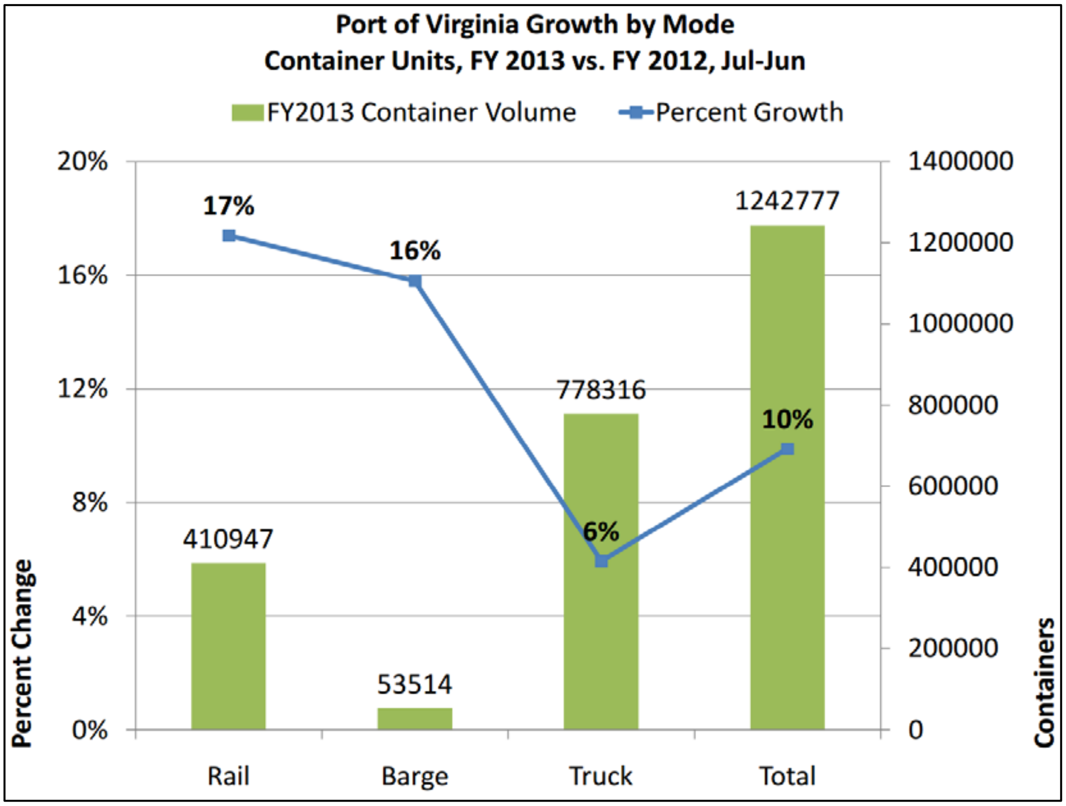

Figure 13. Port of Virginia Growth by Mode (Source: Hampton Roads Partnership (2013))

Even if a port is not directly impacted during and after a storm event, the transport of cargo to/from the port can be. For example, recent storms experienced in HR reduced the use of local roadways affecting cargo movement. Short 1-2 day disruptions due to extreme events are not likely to severely affect bulk facilities but may impact container operations. During peak season, there is less ability for a port to hold cargo on land if it's unable to move off the terminals which could also disrupt ship operations and sailing schedules. To improve operations and increase terminal cargo capacity, the Virginia Port Authority is beginning a $350 million expansion at NIT South to add 400,000 container capacity that will be completed in 2019. In addition, NIT will undergo a major expansion of gate facilities to allow more container access to highway travel.[89]

Condition. This analysis was not able to locate recent information regarding the condition of the ports; however, information from a 2001 workshop was available. In 2001, the U.S. Coast Guard (USCG) conducted a

[88] Hampton Roads Partnership (2013).
[89] Per interview with David White at the Virginia Maritime Association (8/8/2016).

Ports and Waterways Safety Assessment (PAWSA) workshop about Hampton Roads.[90] A group of users and stakeholders evaluated waterway risks in HR. They rated various conditions on a scale of 1 to 9, with 1 being the best possible condition, and 9 being the worst.

Table 25 shows the ratings of various conditions. All were considered acceptable levels of risk, except for Waterway Complexity. The workshop called for improved communications in that area. Waterway Complexity was rated 8.3 because Hampton Roads has many intersecting channels, which leads to crossing traffic. There are also major bends in channels, which reduces visibility.

Table 25. Stakeholder ratings of risk for navigational conditions by risk factor (Source: USCG (2001))

RISK FACTOR	RATING	RISK FACTOR	RATING
NAVIGATIONAL CONDITIONS		**WATERWAY CONFIGURATION**	
WIND CONDITIONS	2.7	VISIBILITY OBSTRUCTIONS	3.7
VISIBILITY CONDITIONS	2.2	CHANNEL WIDTH	3.1
		BOTTOM TYPE	3.9
TIDE AND RIVER CURRENTS	3.8	WATERWAY COMPLEXITY	8.3
ICE CONDITIONS	1.9		

Dredging

Dredging is the act of removing sediment and debris from the bottom of waterways. It is used to both maintain and deepen channels. Sediment from rivers and storms settles on the bottom of waterways and must be removed or else channels will become shallower. Dredging can be an important strategy when considering preparation/responses to flood events.

United States Army Corps of Engineers (USACE) projects in HR waterways.[i]

Project	Description	Costs [ii]
Collection and Removal of Drift	▪ Remove hazards from navigation channel ▪ Five days a week	$998,000
Prevention of Obstructive and Injurious Deposits	▪ Surveillance and supervision operations	$72,000
Deepening	▪ Reconnaissance report on Elizabeth River 45 ft and Southern Branch 40 ft project ▪ Update navigation management plan for HR	$113,000
Maintenance	▪ Dredged Norfolk Harbor Reach and Craney Island Reach to minimum safe level ▪ Maintain critical dike at Craney Island	$8,060,000

[i] USACE (2011).
[ii] Cost is in 2012 dollars.

[90] USCG (2001).

Valuation. Virginia's non-military maritime industry plays a large role in the Commonwealth's economy. In FY 2013, 78.9 million tons of cargo valued at $75.4 billion were moved through Virginia's ports. 16.9 million tons, valued at $18.3 billion, were made in Virginia. 6.7 million tons stayed in Virginia, and created $24.9 billion in spending for goods and services. [91] These figures are for Virginia with HR representing a significant portion of these numbers.[92] The report analyzed six ports: Norfolk, Portsmouth, Chesapeake, Newport News, Richmond, and the Virginia Inland Port in Front Royal. Four of these (Norfolk, Portsmouth, Chesapeake, and Newport News) are in the HR region.

According to a recent report on the economic impacts of POV, [93] in 2013, POV moved 18 million tons of cargo valued at $53.2B; 4.5 M tons of made-in Virginia exports valued at $10.9B; and 3M tons of imported goods that are retained in VA as inputs for commercial production and local consumption valued at $10.4B. Table 26 and Table 27 show the components of the POV impacts on the regional economy and its contribution to the Gross State Product (GSP).

Table 26. Components of POV's Contribution to the Regional Economy (Source: College of William & Mary (2014))

COMPONENTS OF THE POV PORT OPERATIONS	POV SPENDING ($M)	POV VALUE-ADDED (GSP) ($M)	POV EMPLOYEE COMPENSATION ($M)	POV EMPLOYMENT
SHIP & HARBOR OPS, VESSEL LOADING/UNLOADING	$980	$409	$309	3,900
WAREHOUSE/STORAGE	$115	$69	$65	1,412
FREIGHT SERVICE SUPPORT	$435	$189	$187	3,815
TRUCK AND RAIL TRANSPORT	$934	$446	$302	5,001
TOTAL	**$2,464**	**$1,113**	**$862**	**14,128**

Table 27. Total economic impacts of the POV disaggregated by direct, indirect, and induced impacts (Source: College of William & Mary (2014))

COMPONENTS OF POV PORT OPERATIONS IMPACTS	DIRECT ($M)	INDIRECT ($M)	INDUCED ($M)	TOTAL ($M)
REVENUES/SALES	$2, 464	$1,041	$1,721	$5,226
VALUE ADDED (GSP)	$1,113	$645	$1,087	$2,846
EMPLOYEE COMPENSATION	$862	$481	$588	$1,931
TOTAL	**$4, 439**	**$2,167**	**$3,396**	**$10,003**

Putting the economic impact of the POV in the context of the total economy of the Commonwealth, the FY2013 Mason School report on POV estimated the total contribution of POV to the regional economy at $30.5B, or 6.8 percent of the Commonwealth's $448.8B GSP, partly due to the high percentage of the region-

[91] Virginia Maritime Association (2016a).
[92] Per interview with David White at the Virginia Maritime Association (8/8/2016).
[93] College of William & Mary (2014).

wide economic impacts of the port that is generated in HR.[94] Similarly, HR's total employee compensation of $17.5B was calculated at 9.4 percent of VA total employee compensation.

POV's contribution to regional export/import economy is also significant. POV exports some 1.3M tons of export cargo with their production origin in HR. The region's exporters shipped 116,989 container TEUs with a value of $3.2 B. All these tonnage and cargo values accounted for about 29 percent of the Virginia-made export goods. Imports into the HR ports accounted for a lower share of both the volume and value of the Virginia trade activities: HR ports imported 812,961 tons of cargo, valued at $2.6B, accounting for 27.5 percent of the Virginia-used tonnage, and 25.3 percent of its value.[95]

Table 28 shows the percentage distribution of the components of the economic impacts of spending, regional value-added, and employee compensation. The table indicates that the relatively low value-added for the port-related activities stems largely from the fact that although a high amount of cargo handling is done on the imports in HR, the imports have a relatively low overall share in the total regional economy because the value-added from the price markups is low, given the small share of the imports being consumed in HR.

Table 28. Economic impacts of port trade in HR, by economic activity and impact type (Source: College of William & Mary (2014))

ECONOMIC IMPACTS OF PORT TRADE IN HR	DIRECT	INDIRECT	INDUCED	TOTAL IMPACT
SPENDING	30%	21%	36%	29%
VALUE-ADDED	12%	14%	20%	14%
EMPLOYEE COMPENSATION	21%	22%	36%	25%

Another source of asset valuation for the region's port-related assets is the HAZUS-MH database's asset records for 91 port facilities in Norfolk, indicating a combined port-asset valuation of $181,727,000. These HAZUS-MH data on HR seaports provide an inventory of port traffic and asset valuation for waterfront structures, cranes, cargo handling equipment, warehouses, and fuel facilities. HAZUS-MH also contains records of three ferry facilities, with a combined valuation of $3,993,000. The HAZUS-MH port database was developed from the calendar-year 2000 database of Port and Waterway Facilities, maintained by the U.S. Army Corps of Engineers (USACE) Institute for Water Resources Navigation Data Center (Ports and Waterways Division). The 2015 version of the USACE database includes 117 port facilities, representing an increase of 26 port facilities from the 2000 HAZUS-MH data. This suggests that new port facilities may have been added in the intervening 15 years. As with the down-side bias in estimated values of the regional bridge and rail assets, the above HAZUS-MH valuation of the POV is likely to be understated.

[94] The sources of data for the POV report were data from the Bureau of Economic Analysis (BEA) sectoral output that were used to calculate the total contribution of the HR Metropolitan Statistical Area (MSA) and POV to the regional economy.
[95] Data sources for these estimates included data from PIERS (Port Import Export Reporting Service) – with data on tonnage, TEU, origin-destination, and harmonized commodity codes – and other DOC International Trade Administration (ITA), BEA, and Census Bureau databases.

Pipelines

Ownership and Inventory. Historically, natural gas consumed in Hampton Roads has been transported by two primary interstate pipelines: Columbia Gas transmission feeding South Hampton Roads, and Virginia Natural Gas (VNG) supplying North Hampton Roads. Local distribution within Norfolk and most of HR itself is provided by VNG. [96] Figure 14 shows pipeline assets of Columbia (in green) and VNG (in blue and red) serving HR.

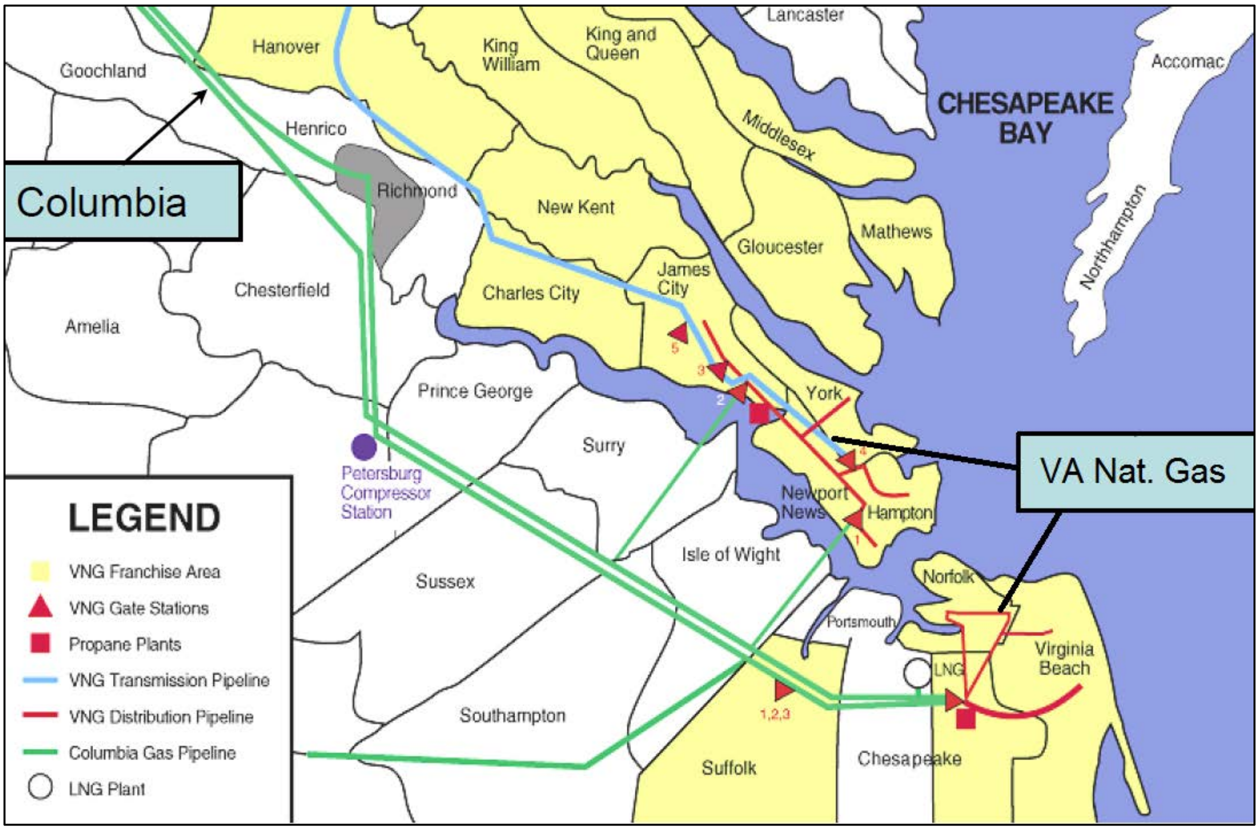

Figure 14. HR pipeline infrastructure (Source: Virginia Natural Gas)

Use. The geographic division created by the HR waterbody and resultant two non-contiguous gas distribution systems (Northern and Southern)[97] exposed HR to natural gas supply and price vulnerabilities. This is because on any peak day, each system was fed by a single interstate pipeline (VNG in the North, Columbia in the South).[98] Until recently, because South HR was only served by one major pipeline, Norfolk and neighboring municipalities had grown dependent on back-up systems (especially on the coldest heating days) fueled by propane and/or liquefied natural gas (LNG) transported in by truck.

[96] Virginia Department of Mines, Minerals and Energy (2014).
[97] The Southern system includes the areas of Norfolk, Virginia Beach, Chesapeake and Suffolk in south side Hampton Roads. The Northern system includes Hampton, Newport News, Poquoson, York, James City, Williamsburg, New Kent, and Charles City on the Peninsula, as well as Hanover and King William counties.
[98] Virginia Natural Gas (n.d.).

To address this supply constraint, VNG developed the Hampton Roads Crossing (HRX) pipeline project to connect the two Northern and Southern HR gas distribution systems by way of a new pipeline water crossing across HR Harbor (Figure 15).

Figure 15. HRX pipeline (Source: Virginia Natural Gas)

The HRX pipeline was completed in 2010, providing substantial gas supply and reliability benefits to residential and business sectors in the HR region, as well as ensuring a more stable gas supply to military facilities in the Southern distribution system including Norfolk Naval Station, Oceana Naval Air Station, Little Creek Amphibious Base, Dam Neck Naval Training Station and Fort Story. The HRX pipeline and associated compressing equipment has also provided increased gas access to some of Dominion Virginia Power's gas-fired electric generating plants in central Virginia. The HRX has also opened up HR's access to a broader geographical range of natural gas supplies, including the Marcellus Shale, Rockies, Mid-Continent, Gulf Coast and other locations (see Table 29 for additional description of the HRX pipeline).[99]

Table 29. Description of the Hampton Roads Crossing (HRX) Pipeline (Source: Virginia Natural Gas website)

HAMPTON ROADS CROSSING (HRX) PIPELINE	
COMMISSIONED:	The Hampton Roads Crossing (HRX) Pipeline was completed and put into service in 2010.
OWNER/OPERATOR:	Virginia Natural Gas
CONNECTS:	Connects gas distribution systems in Northern Hampton Roads (Newport News, Hampton) and Southern Hampton Roads (Norfolk, Portsmouth, Virginia Beach).
LENGTH:	21-miles of 24in. pipe: • 7 miles in Hampton/Newport News • 4 miles in Norfolk • 10 miles of water and island crossing o 4 mile harbor crossing o 4.5 miles on Craney Island o 1.5 mile Elizabeth River crossing
CAPACITY:	Over 100,000 dekatherms natural gas per day

Condition. This analysis was not able to locate recent information regarding the condition of the pipeline.

Valuation. This analysis was not able to locate recent information regarding the valuation of the pipeline.

1-1-2 Service Operations

Freight Network: Trucking and Multi-modal Operations

Hampton Roads Transportation Planning Organization (HRTPO) conducted a study in 2012 on the HR regional freight.[100] The study identified the regional freight movement patterns and the commodity-flow data for all modes, including trucking, rail, and water. The source of the HRTPO's data for the region's freight movements was the Commodity Flow Survey (CFS) database used in the FHWA Freight Analysis Framework (FAF) data on Origin-Destination (O-D) freight movements by mode, weight, and value for existing (2010) and projected 2040 conditions. Table 30 summarizes the four freight transfer facilities in Norfolk. This report's Sea Ports and Waterways' section provides some data on freight container movement in the Port of Virginia. Further

[99] Virginia Natural Gas (n.d.).
[100] HRTPO (2012c).

information may be collected to analyze the economic value of the trucking and rail industry in HR for the transportation of goods and services.

Table 30. Freight facilities in Norfolk (Source: 2015 National Transportation Atlas Database)

NAME OF FREIGHT FACILITY	MODES
NORFOLK INTERNATIONAL AIRPORT	Air and truck
NORFOLK SOUTHERN BULK TRANSFER TERMINAL	Rail and truck
NORFOLK WAREHOUSE DISTRIBUTION CENTERS, INC.	Rail and truck
NORFOLK INTERNATIONAL TERMINALS	Port, rail, and truck

Transit

Hampton Roads Transit (HRT), currently serves the Southside and Peninsula areas of Hampton Roads, consisting of the cities of Hampton, Norfolk, Newport News, Portsmouth, Suffolk, Chesapeake, and Virginia Beach. Major HRT assets include a light rail transit system in downtown Norfolk (The Tide), an expansive bus service network, and ferry services.[101] The following details each of these:

Light Rail Transit (LRT) – The Tide

- The Tide light rail transit system opened its "starter line" in 2011.
- The current line includes 11 stations and extends 7.4 miles through downtown Norfolk (Figure 16).
- Operates 9 light rail transit vehicles.
- Averages over 1.65M passenger trips per year.[102]
- The majority of the line is ¼ mile or less from the waterfront; several stations lie within 800 ft from the water, including one less than 1/10 mi from the coastline. The light rail track itself crosses creeks and rivers in multiple locations.[103]
- HRT is examining alternatives analyses for potential extension of The Tide to Norfolk Naval Base, Old Dominion University, Norfolk International Airport, and Virginia Beach.

[101] HRT (n.d.)..
[102] HRT (2014).
[103]Analysis based on Google Earth imaging.

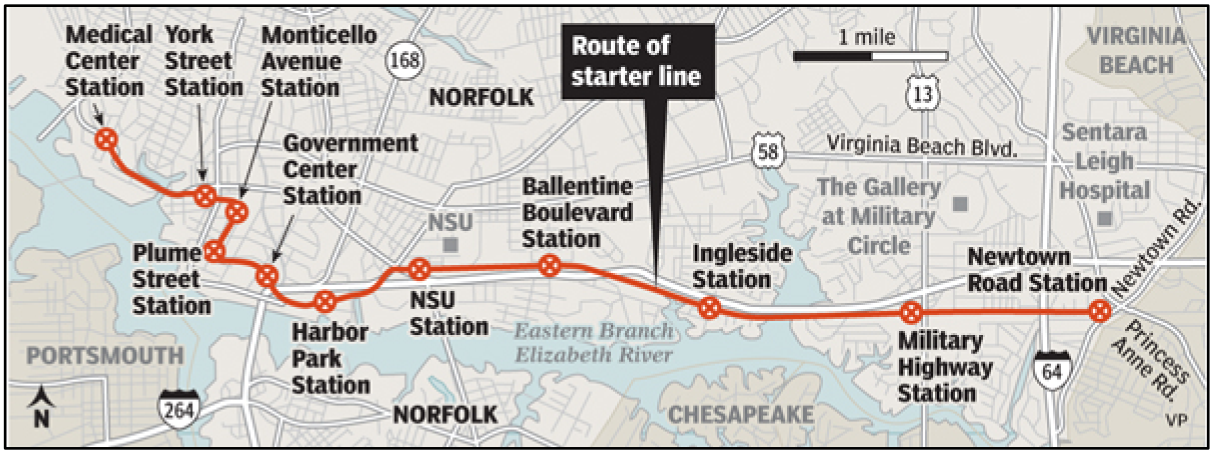

Figure 16. The Tide light rail system (Source: www.hamptonroads.com)

Bus Services

- Provided over 17.9 million passenger trips in FY14 to people in Chesapeake, Hampton, Norfolk, Newport News, Portsmouth and Virginia Beach. [104]
- Fleet includes 302 buses (255 diesel buses, 37 hybrid buses and 10 trolley-style buses).[105]
- 3,500 bus stops & 199 bus stop shelters.
- Includes six major transfer centers – four of which are within a ½ mile of the coast.[106]

Ferry Services

- Ridership typically averages ~350,000 ferry passenger trips per year.[107]
- Operates routes between Norfolk and Portsmouth on the Elizabeth River (Figure 17).
- Includes four ferry docks.
- Fleet includes three 150-passenger ferry vessels.
- Waterfront parking facility (Portsmouth).

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[104] HRT (2014).

[105] As of August 2011.

[106] Analysis based on Google Earth imaging.

[107] HRT (2014).

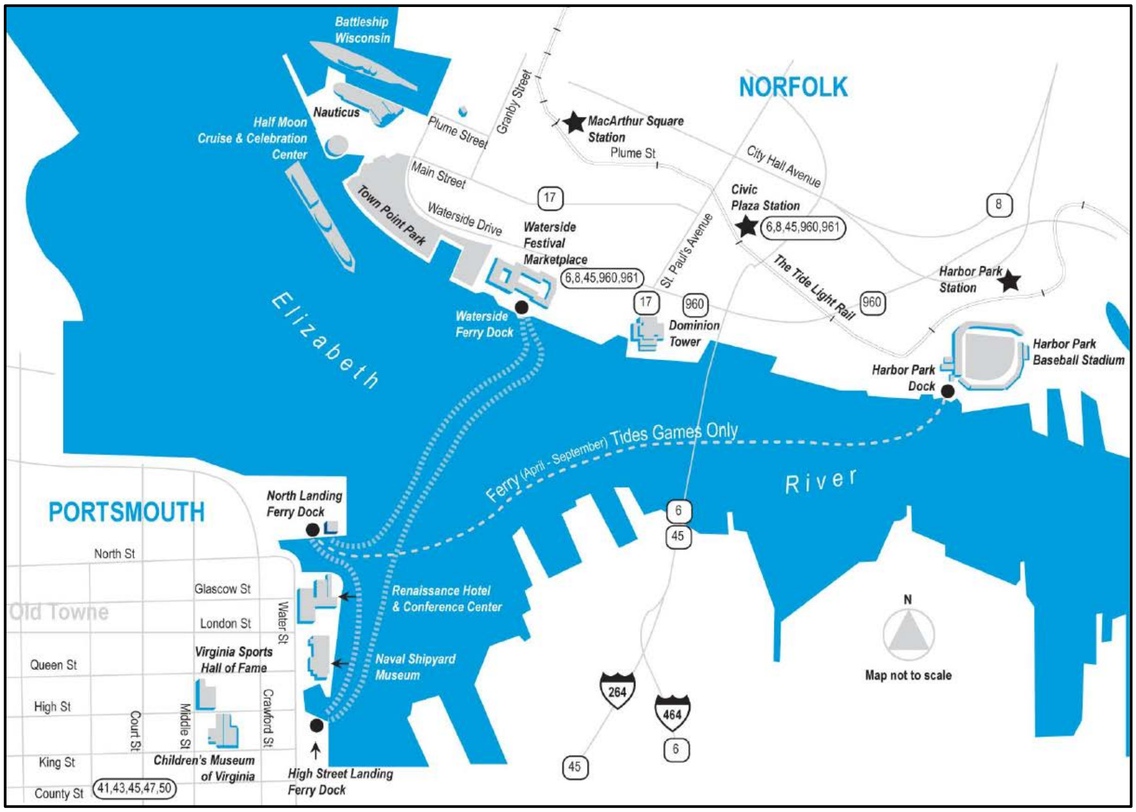

Figure 17. Hampton Roads Ferry Routes & Docks (Source: Hampton Roads Transit)

1-2 DATA FOR ANALYZING INDIRECT ECONOMIC IMPACTS ON THE MULTIMODAL TRANSPORTATION SYSTEM

To fully capture the extent of indirect losses associated with loss of transportation services or changes in the current transportation system in response to implementation of adaptive strategies, we need to quantify the climate-related losses associated with costs of business interruption, reduced access to critical infrastructure, social vulnerabilities arising from poverty and lack of transportation access, and associated with right-of-ways. To consider this, this section discusses HR (including Norfolk) economy, demographics, and critical infrastructure. In addition, right-of-way considerations and indices used to identify vulnerable populations are also introduced.

1-2-1 Economy

Employers. The region is home to 16 federal agencies, including numerous Department of Defense (DOD) installations and the world's largest naval station, Naval Station Norfolk. Figure 18 shows the percent of employment by industry in the Hampton Roads Metropolitan Statistical Area (MSA). In 2011, the military accounts for 9.4 percent of all employment in HR.[108]

[108] HRPDC (2013).

By sector, employment change in the 2009-2014 shows the best-performing sector to be Professional and Business Services at a growth rate of 28.36 percent; and the worst-performing sector the Information Sector at a rate of -30.13 percent.[109]

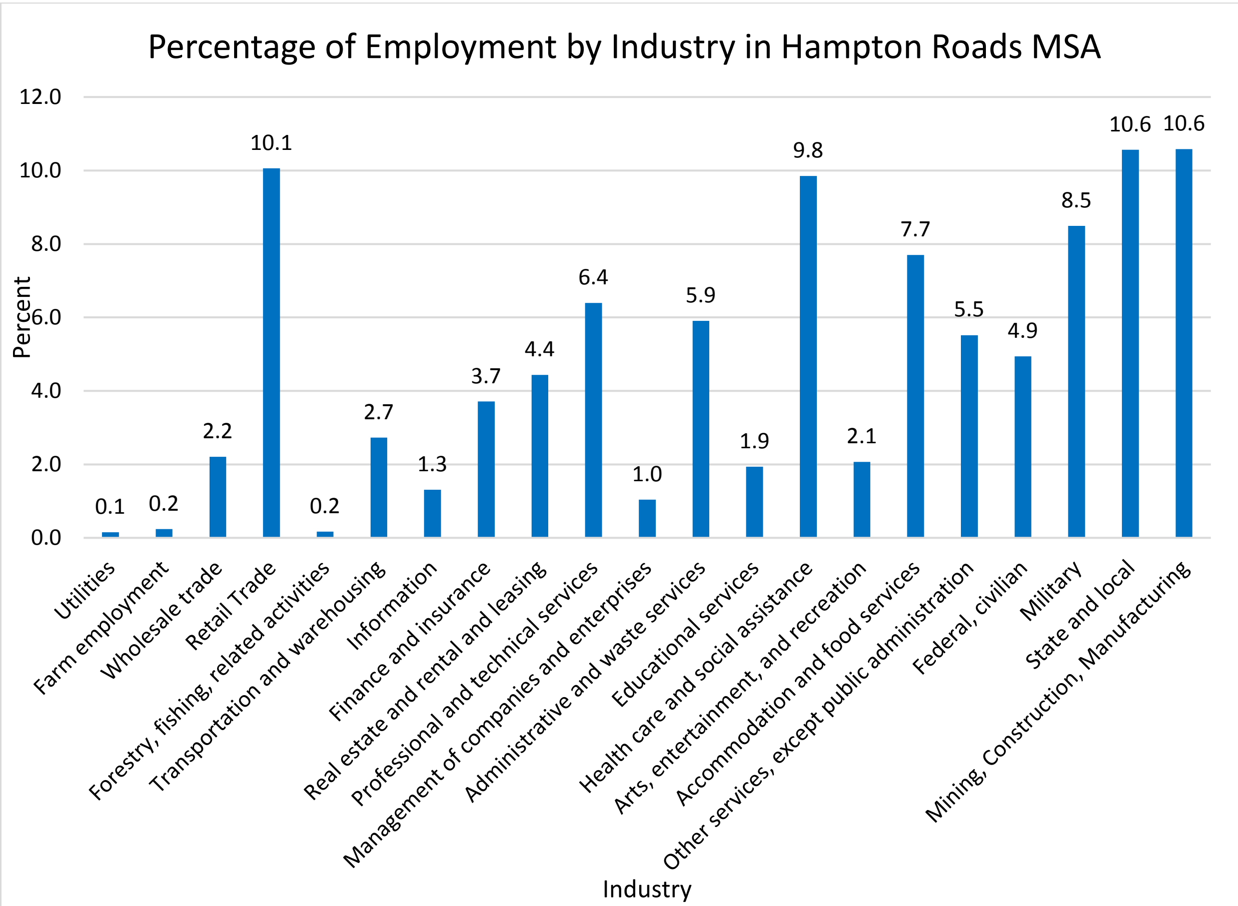

Figure 18. Percentage of employment by industry in Hampton Roads MSA for 2014 (Source: data from HRPDC's Hampton Roads Data Book: Employment)

Figure 19[110] shows the Norfolk share of HR employment by industry (comprising mostly around 10-15 percent of the employment in each sector), highlighting the significant share of military employment in HR is located in Norfolk (largely attributed to Naval Station Norfolk), accounting for close to a third of the employment.[111]

[109] ODU (2015).
[110] HRPDC (n.d.).
[111] Sandia National Laboratories (2016).

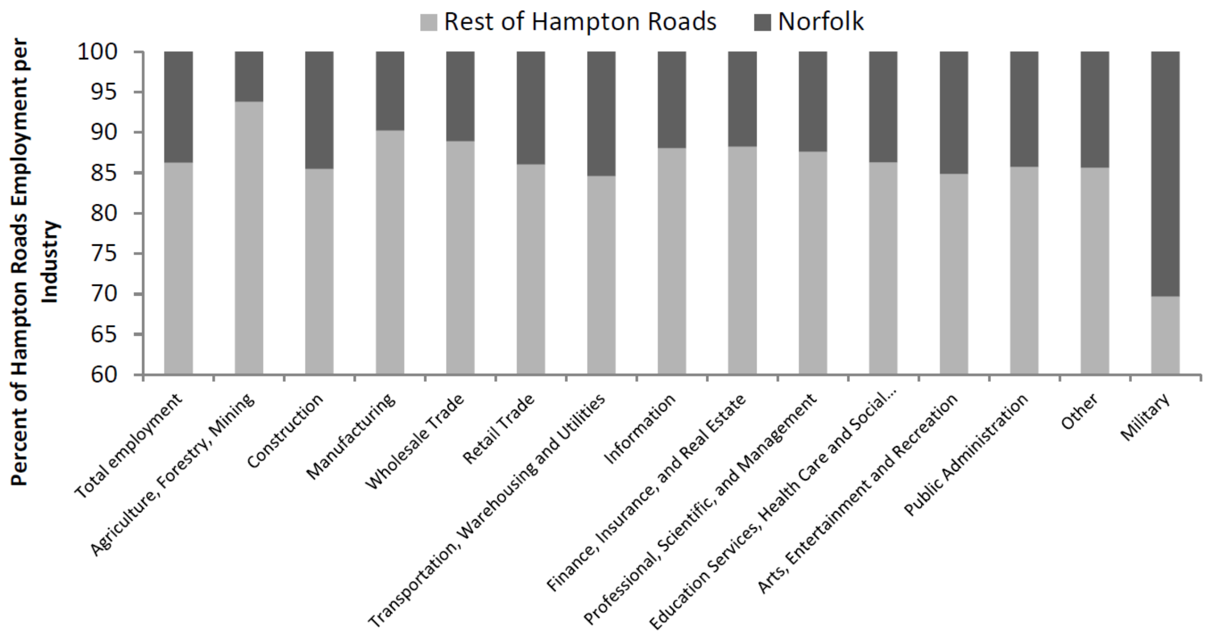

Figure 19. Norfolk share of total HR employment by industry (Source: data from Sandia National Laboratories (2016), U.S. Census Bureau)

With respect to the military's large share of the Norfolk economy, recent fluctuations in military budget and expenditures have substantially contributed to changes in Norfolk's employment levels. The significance of the defense industry in the economic stability of the HR region in general, and in Norfolk in particular, is further examined below.

Employment Rates. The HR region's total employment in 2013 was 720,000. Norfolk's employment of 136,300 comprises 19 percent of the region's total employment (compared to its population share of 14.6 percent). HR has experienced a lower rate of employment growth compared to the rest of Virginia (at near zero growth rate compared to 1.72 percent growth in Northern Virginia and 0.99 percent statewide), which has in part been attributed to its lower business startup rate.[112] This also corresponds to a regional slow-down in population growth, which is in large part due to the loss of population in Norfolk.[113]

Military. The military facilities located in HR and Norfolk are a key economic driver in the region and are highly vulnerable to coastal flooding and SLR threats. Table 31 lists employment data for six of the key DOD

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[112] Hampton Roads Partnership (2013) indicates an improving situation, with an increase in the number of startups per 10,000 residents from 5.0 in 2003 to 9.4 in 2012 (with a peak of 10.7 during the pre-recession year of 2007). The reports notes that HR has the second highest *Employment to Household Ratio* in VA (1.5), second after Northern VA (1.7). A jobs to housing ratio greater than 1 indicates that more jobs than housing exists within the jurisdiction; a ratio of 2:1 is typically promoted as an ideal balance that provides jobs and retail opportunities for all the population within the area (thus reducing the need to commute to outside the region for work).

[113] VTrans (2010). The report states that net migration in Norfolk (comprised of domestic and international migration) has declined or remained unchanged over the last decade.

facilities in or around Norfolk, reporting over 72,000 Active Duty personnel, almost 8,000 Reserves, almost 34,000 civilian employees, and over 13,000 contractors, amounting to a total direct employment of 127,022.

Table 31. Norfolk Area Military Facilities. (Source: Vanderley 2016)

NORFOLK AREA MILITARY FACILITIES	ACTIVE DUTY	RESERVES	CILIVIAN	CONTRACTOR
NAVAL STATION NORFOLK	42,997	1,462	13,468	7,037
JOINT EXPEDITIONARY BASE LITTLE CREEK-FORT STORY	10,422	4,547	3,222	723
NAVAL AIR STATION OCEANA/DAM NECK	9,724	980	2,786	3,080
NORFOLK NAVAL SHIPYARD	804	96	9,921	1,553
NAVAL WEAPONS STATION YORKTOWN	1,379	186	1,103	453
NAVAL SUPPORT ACTIVITY HAMPTON ROADS	6,942	445	3,266	456
TOTAL	**72,268**	**7,716**	**33,736**	**13,302**

Hampton Roads Planning District Commission (HRPDC) conducted an economic impact analysis to quantify the direct and indirect economic impacts of DOD employment in HR. The study team used the Regional Input-Output Model System (REMI) and Computable General Equilibrium (CGE) methodology to estimate the full economic impacts, direct and indirect employment impacts and contribution to the HR region's earnings and Gross Domestic Product (GDP), as summarized in Table 32 (see Part 2 of this report for model for description of REMI model and other I-O and CGE methodologies). The REMI model measured the significant multiplier effect of military employment in HR, as indicated by the model's estimate of an employment multiplier of 1.873 for the military sector. This multiplier of 1.873 means that for every 1,000 direct defense employees in HR, 873 indirect and induced jobs are created inside and outside the region.

Table 32. Economic Impact of Military Personnel in Hampton Roads (Source: HRPDC (2013))

MILITARY PERSONNEL IMPACT CATEGORY	TOTAL HAMPTON ROADS ECONOMIC IMPACT
DIRECT EMPLOYMENT	92,962
INDIRECT AND INDUCED EMPLOYMENT	81,200
TOTAL EMPLOYMENT	174,162
TOTAL EARNINGS IMPACT	$10.9 Billion
GROSS REGIONAL PRODUCT	$16.6 Billion

Another illustration of the extent of military economic impact in Norfolk is the Langley Air Force Base. In 2006, Langley's employment and spending profile was as follows: direct agency procurement and spending: $722M;

direct spending by visitors: $5.4M; indirect expenditures: $378M; induced expenditures: $1.2B. Total jobs created were 20,649 (direct: 7,529; indirect: 2,985; induced: 10,135).[114]

VDOT Roadway User Costs. VDOT has a methodology for calculating roadway user costs for delays to travelers in response to closing a road or other asset within the transportation system. Costs include such factors as lost wages and extra fuel consumption. This methodology has been adopted by HR. Further discussion is warranted to determine the availability and best use of this work in this study.[115]

1-2-2 Demographics

Income. According to the 2015 *State of the Commonwealth Report*[116] the median household income in 2013 in Norfolk was $44,747, compared to $62,666 for the Commonwealth of Virginia.[117] Table 33 compares median and real income levels (adjusted for cost-of-living) in Norfolk, the Commonwealth of Virginia, and the United States in 2013.

Table 33. Income and cost of living in 2013 for Norfolk, Commonwealth of Virginia, and the U.S. (Source: Old Dominion University (ODU) (2015); Norfolk, City of (2014))

LOCALITY	MEDIAN INCOME 2013	NUMBER OF HOUSEHOLDS	COST-OF-LIVING INDEX (COLI)	REAL MEDIAN INCOME, 2013
CITY OF NORFOLK	$44,747	85,557	112.9	$39,634
HAMPTON ROADS MSA*	$56,161	628,572		
COMMONWEALTH OF VIRGINIA	$63,907	3,055,863	103.2	$61,925
UNITED STATES	$53,046	116,291,033	100	$53,046

**Data for Hampton Roads is from the 2010 census*

In 2011, HR had the largest percentage of residents in Virginia with incomes below the federal poverty level.[118] The HR poverty rate was 12.4 percent, compared to the rate of 6.8 percent in Northern Virginia, and the overall VA rate of 11.5 percent.[119] In Norfolk the median household income is about $44,743, compared to about $52,000 for the Commonwealth as a whole. Only 45.4 percent of homes are owner-occupied in Norfolk, which is lower than the percentage of owner-occupied homes in the Virginia Beach—Norfolk—Newport News MSA (63.1 percent).[120]

The Norfolk-Virginia-Beach-Newport News MSA had a lower rate of GDP growth, 0.31 percent average annual growth from 2009 to 2014, compared to the Washington DC-Arlington-Alexandria-Maryland MSA, 1.00

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[114] NASA (2006).
[115] Per communication with John Mazur at FHWA.
[116] ODU (2015).
[117] The ODU report highlights the significance of applying the cost-of-living index (COLI) factor to arrive at real median income. It notes that in 2013 Virginia's real income in 2013 ($63k, with a relatively low COLI of 103) was far higher than high-income cities such as Manhattan, which has a nominal median income of $69k, but with a COLI of 185, a "real income" of just $38k. Similarly, for Brooklyn, NY, the nominal income was $46k; making the real income $24,500 after applying the COLI of 188.
[118] Hampton Roads Partnership (2013).
[119] The Hampton Roads Partnership (2013) reports that in 2011, HR had a per-capita income of $11,484 for an individual.
[120] Norfolk, City of (2014).

percent average annual growth.[121,122] Influencing the MSA salaries are the business cycle, the mix of industries, and other factors such as a slowdown in the growth of the defense industry. As noted above, HR is part of Norfolk–Virginia Beach-Newport News MSA. However most of the income statistics reported in the study are for Norfolk.

1-2-3 Critical Infrastructure Facilities

Further underscoring the difficulty of determining the extent of indirect costs of climate-related disruption is the intermingling of the private assets with the critical infrastructure facilities. The National Oceanic and Atmospheric Administration's (NOAA's) Coastal Economy Database for Norfolk contains information on 413 "critical facilities" located in Norfolk—schools, hospitals, fire stations, police departments, dams, and transportation infrastructure assets—that represent both asset vulnerability and also rank high on a prioritization scale when emergency conditions prevail. Table 34 lists these facilities that show the distinct public-goods character of many Norfolk critical infrastructure assets.

Table 34. Critical facilities in Norfolk (Source: NOAA Coastal Economy Website)

NORFOLK CRITICAL FACILITIES	FACILITY COUNT
MEDICAL FACILITIES	7
COMMUNICATION TOWERS	4
DAMS	1
EMERGENCY CENTERS	1
FIRE STATIONS	2
HAZARDOUS MATERIALS FACILITIES	28
HIGHWAY BRIDGES	173
POLICE STATIONS	11
PORT FACILITIES	91
POTABLE WATER FACILITIES	3
SCHOOLS	89
WASTEWATER FACILITIES	3

1-2-4 Right-of-Way Considerations

The term Right-of-way (ROW) is defined as "any real property, or interest therein, acquired, dedicated, or reserved for the construction, operation, and maintenance of a highway."[123] The acquisition of real property interests is a fairly typical activity that is required in order to construct many transportation projects, or

[121] In May 2015, the state unemployment rate was 4.5%, compared to the US average of 5.1%, showing a lower rate from the peak unemployment rate of 7.4% in 2010.
[122] ODU (2015).
[123] 23 U.S.C. (2012).

expand an existing transportation facility outside of the limits of its existing footprint. This activity must be taken into account early in the project planning process in order to ensure timely project delivery.

Depending on the impacts of a given project, the acquisition of all necessary real property rights (and the potential relocation of property owners and tenants) can become a major project cost. This applies to all Federal or Federally-assisted projects, including transportation projects associated with SLR and coastal flooding adaptation. This is also true for projects involving the expansion or relocation of ROWs for roads, bridges, or highways, and for impacts to access to existing uses, wetlands, and ROW-related stormwater management.

The acquiring agency must comply with all applicable provisions of 42 USC Ch. 61: Uniform Relocation Assistance and Real Property Acquisition Policies for Federal and Federally Assisted Programs ("Uniform Act" or "UA") whenever there is Federal funding participation in any phase of a public project. The acquisition of real property interests in connection with any Federal or Federally-assisted program or project must be carried out in accordance with the Uniform Act. This law is intended to provide for the uniform, fair and equitable treatment of persons whose real property is acquired or who are displaced in connection with Federally funded projects.

The goal should always be to acquire the necessary property rights through amicable negotiation, but realistically, most large or complex transportation projects involve the acquisition of at least some property rights through the power of eminent domain, via the condemnation process. All project cost estimates should include the projected acquisition cost of the necessary property rights (and possible condemnation costs) and the costs to relocate all displaced property owners, tenants and businesses.

It should also be noted that in addition to cost to acquire sufficient ROW for a project, an acquiring agency may be required to compensate some impacted property owners for "legally-compensable damages", occurring as a result of the project. Whenever the amount of damages is determined through the condemnation process, the level of financial risk is heightened and it is advisable to factor in that variable in some manner.

Very often, the realty or ROW impacts of a project will require the relocation of existing utilities such as water, sanitary sewer, power, cable, telephone and other utilities. Regardless of whether these are public or private utilities, their relocation must be coordinated with road/bridge/highway work.[124] There may also be indirect costs related to these other services that rely on the transportation network under an "as-is" condition. For example, if electrical infrastructure is buried underneath the roadway, widening or raising the roadway may result in additional maintenance costs to the electrical infrastructure.[125] These are indirect costs that are not generally considered in a traditional transportation economic analysis but can have significant impacts on the bottom line and operations for the utility industry. The transportation ROW-related costs in this regard are

[124] Per communications and comments from Henry R. ("Speaker") Pollard, V, a partner with the law firm of Williams Mullen and chair of its Coastal Flooding and Resiliency practice group.
[125] Per communication with Robert Martz, Hampton Roads Sanitation District (HRSD).

only part of the pending and growing infrastructure costs associated with already needed repairs, replacements and expansions for roads/bridges/highways, water supply and treatment systems, stormwater management systems, and wastewater/sanitary sewer collection and treatment systems.[126]

It should also be noted that the need to ensure sufficient ROW or accessibility is not limited to transportation agencies or utility providers. Some private property owners and even other governmental or institutional facility owners and operators seeking to plan for, adapt or defend against sea level rise and flooding impacts may over time need to expand their own property holdings or interests to install adaptive or defensive measures or otherwise improve the quality of their property's access. As a result, these landowners can be expected to face their own needs and challenges to secure or improve their own ROWs and site accessibility to ensure ingress and egress and otherwise to protect their property. These efforts may interconnect with, or perhaps even conflict with, transportation ROW projects. While such landowner needs and efforts may not be known with certainty at the outset, the identification and engagement of potentially-impacted stakeholders should be pursued as the project planning stage moves forward. Accurately forecasting the costs of such ROW considerations over a transportation project's useful life is no small task. To a great extent, such accuracy depends greatly on the accurate projection of sea level rise and coastal flooding impacts, as well as an accurate assessment of current and expected land uses. In turn, it is important for federal and other transportation agencies to coordinate closely with local and regional planning officials and to stay current with and utilize appropriate projections of such impacts early in the project planning process.[127]

1-2-5 Vulnerable Populations.

USDOT policy supports including inequality and environmental justice issues when evaluating climate change impacts and adaptation.[128] A few sources are available to consider this. National Oceanic and Atmospheric Administration (NOAA) has developed Social Vulnerability Index (SoVI), a tool that measures a region's vulnerability to natural hazards by analyzing the 2010 Census-block or census-tract-level data on incomes and poverty rates to identify the vulnerabilities of poor and disadvantaged communities to climate disruptions. The "Social Vulnerability Index" may be an indicator of a community's need to plan for low-income populations and lack of access to jobs as a threat multiplier for disruptive climate events. To this extent, indirect costs of SLR and flooding are harder to quantify because they are not based on direct measures of damaged property. Figure 20 and Figure 21 illustrate the overall SoVI index and the theme-specific data for Norfolk.

Another metric for identifying the risks posed by poverty and income inequality[129] is a region's Gini Coefficient.[130] The coefficient, as an index of income inequality, serves as a measure of how significant rates of income inequality can prove to be a major risk multiplier for sensitivities to climate risks. The Gini Coefficient is calculated with a value between 0 and 1, with 0 indicating absolute equality of income, and 1

[126] Per communications and comments from Henry R. ("Speaker") Pollard, V.
[127] Per communications and comments from Henry R. ("Speaker") Pollard, V.
[128] FHWA (2016b).
[129] Income inequality refers to the range to which income is distributed unevenly across the population.
[130] ODU (2015).

indicating total inequality; equivalent of a single person capturing all income benefits. Norfolk's Gini coefficient is 0.473, higher than the Virginia Commonwealth rate of 0.461, and the US rate of 0.469.[131] Norfolk's demographic profile suggests similar indications of the city's below-average economic status.

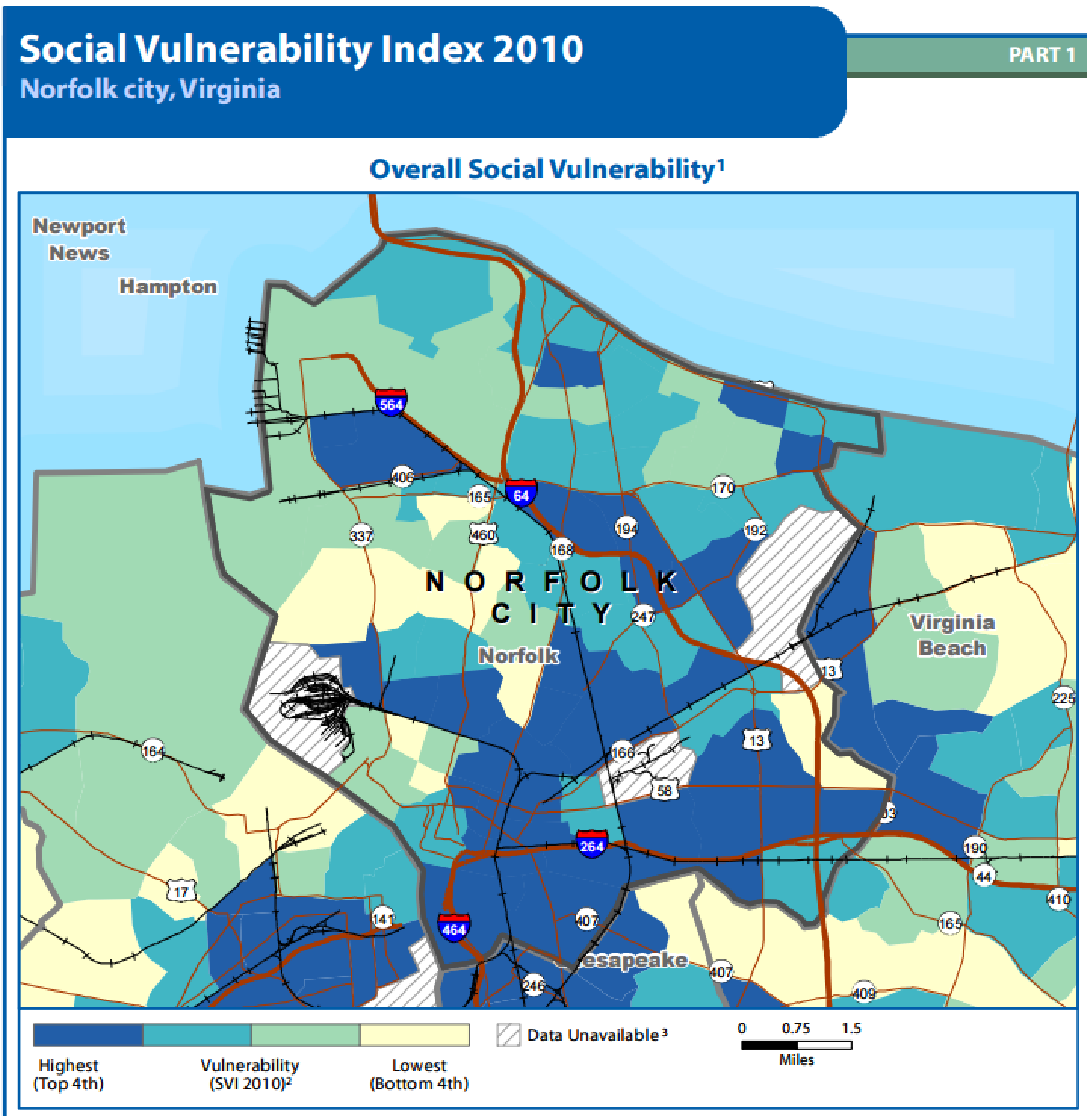

Figure 20. Social Vulnerability Index for Norfolk, Virginia; highest vulnerability is shaded in blue and lowest vulnerability is shaded in yellow (Source: http://svi.cdc.gov/PreparedCountyMaps.html)

[131] As a point of comparison, Philadelphia had a ratio of 0.5020; New Orleans a ratio of 0.5521; and Manhattan a ratio of 0.5994.

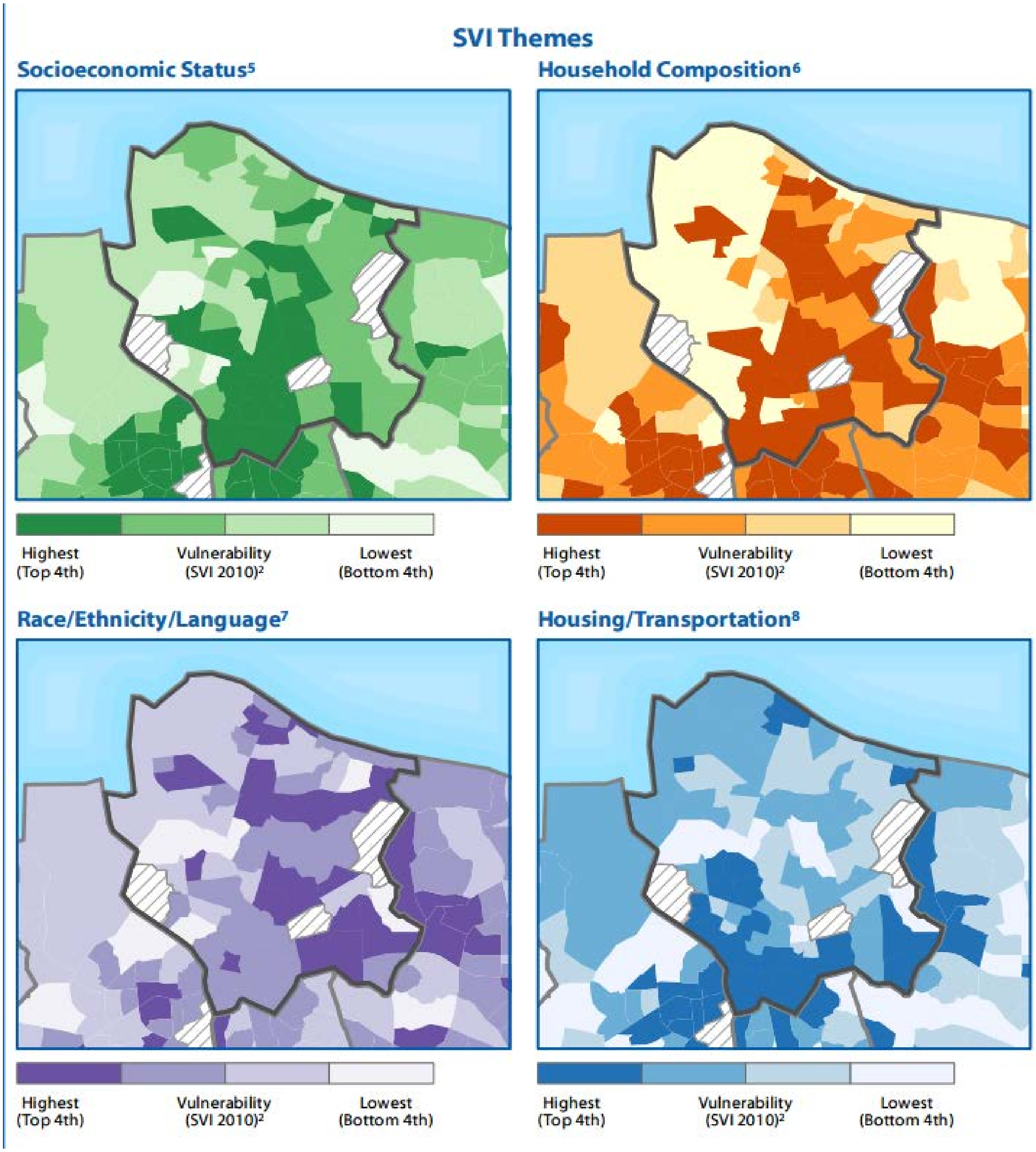

Figure 21. Theme-specific data on social vulnerability in Norfolk from the Social Vulnerability Index; darker colors reflect higher vulnerability (Source: http://svi.cdc.gov/PreparedCountyMaps.html)

1-3 – DATA DESCRIBING ASSET EXPOSURE TO CLIMATE STRESSORS

To describe HR region's asset condition, we need to identify the climate stressors and quantify the scale of the damages and disruption in key transportation functions. Note that the purpose of this section is not to present a formal assessment of all climate-related infrastructure risks in HR or Norfolk. Instead, the purpose is to present high level findings of the available studies and data.

Climate stressors are defined as climate or weather events that pose a threat to the transportation system.[132] The following climate stressors have been identified as concerns for HR: (1) sea level rise (SLR), (2) storm surge due to hurricanes and nor'easters, (3) extreme heat days, and (4) heavy precipitation events.

For assessing how various manifestations of climate change impact the transportation infrastructure, there a number of possible climate stressors that can be considered. Table 35 provides examples of impacts of climate stressors on transportation assets. Of these climate stressors, SLR and storm surge are the greatest concern amongst HR stakeholders.

Table 35. Example of climate stressors and damage mechanism on transportation infrastructure (Source: USDOT (2012b))

STRESSOR	ASSET TYPE	DAMAGE MECHANISM
INCREASED PRECIPITATION	• Culvert and storm drain network	• Flooding
SEA LEVEL RISE	• Navigable waterway bridge	• Clearance for navigation
	• Bridge approach embankment	• Slope erosion
	• Coastal roadways, highways, rails, tunnels	• Flooding
	• Pipelines	• Saltwater intrusion causing corrosion
HIGHER STORM SURGE	• Bridge abutment	• Abutment scour
	• Bridge segment	• Wave forces/bridge pier scour • Overtopping/slope erosion
	• Coastal roadways and highways	• Overtopping/slope erosion
TEMPERATURE CHANGE	• Rail	• Equipment failure • Buckling of rail
	• Roadway and highways	• Rutting and shoving of pavement

[132] National Cooperative Highway Research Program (n.d.).

1-3-2 Coastal Flooding

Recurrent flooding

Recurrent flooding is generally associated with high tides that occurs with some frequency over land, also termed "nuisance flooding."[133] This form of flooding can be considered low-magnitude/high probability events. There are coastal areas throughout HR that are susceptible to frequent minor-to-moderate shallow coastal flooding events (see Figure 22). For example, Norfolk currently experiences nuisance flooding on a monthly basis.[134]

Nuisance flooding, according to NOAA, "has increased on all three U.S. coasts, between 300 and 925 percent since the 1960s."[135] These events are likely to have significant cumulative impact on the built environment and social/ecological systems over the coming decades.

Recurrent Flooding Example: Sandbridge Resort Community

The Sandbridge resort community consists of 5 miles of secluded beach located adjacent to Back Bay National Wildlife Refuge (BBNWR), an 8,000-acre freshwater refuge with large sand dunes, maritime forests, and freshwater marshes. Sandbridge is a very important community to the City of Virginia Beach as it is a popular vacation destination for tourists and residents. It consists of approximately 280 households and has 44 businesses with 238 employees. However, Sandbridge is not easily accessible with only one public roadway approximately 5.3 miles long connecting the community, Sandbridge Road. Sandbridge Road has a range of 5,500 to 17,000 vpd (vehicles per day) and is an evacuation route. However, Sandbridge Road, among other roadway safety concerns, experiences nuisance flooding. The 100-year FEMA base elevation for that area is 4.0 feet above the North American Vertical Datum of 1988 (NAVD 88). Sandbridge Road elevation ranges from 1.0 ft to 3.5 ft, which does not even meet current standards. Without a modification, the existing low-lying elevation of the roadway would continue to be problematic causing re-occurring flooding which will only worsen with sea level rise.

Source: Adapted from communication with Phil Pullen, P.E.

[133] NOAA (2014a).
[134] NOAA (2014b).
[135] NOAA (2016).

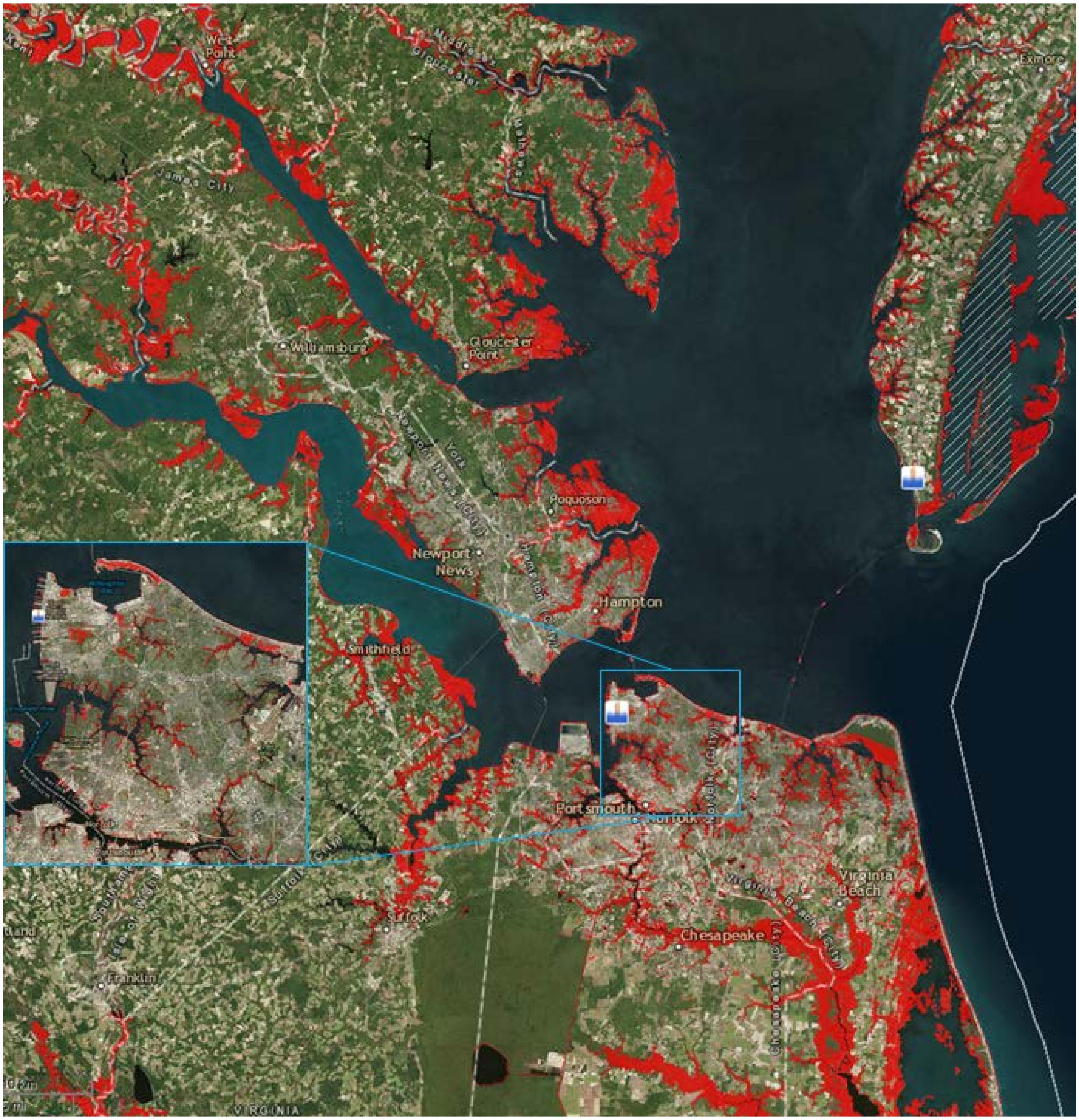

Figure 22. Areas currently susceptible to shallow coastal flooding in Hampton Roads, inset Norfolk (Source: NOAA Sea Level Rise Viewer)

Figure 23 identifies the number of flood events for road segments over about a 4 year period. It is not known from Figure 23 what caused the flooding (e.g., extreme event or high tide), but those road segments that experience a higher level of flooding may be in areas prone to recurrent flooding. The roadways that experience more frequent flooding align somewhat with the areas currently susceptible to shallow coastal flooding (though this is a bit difficult to distinguish).

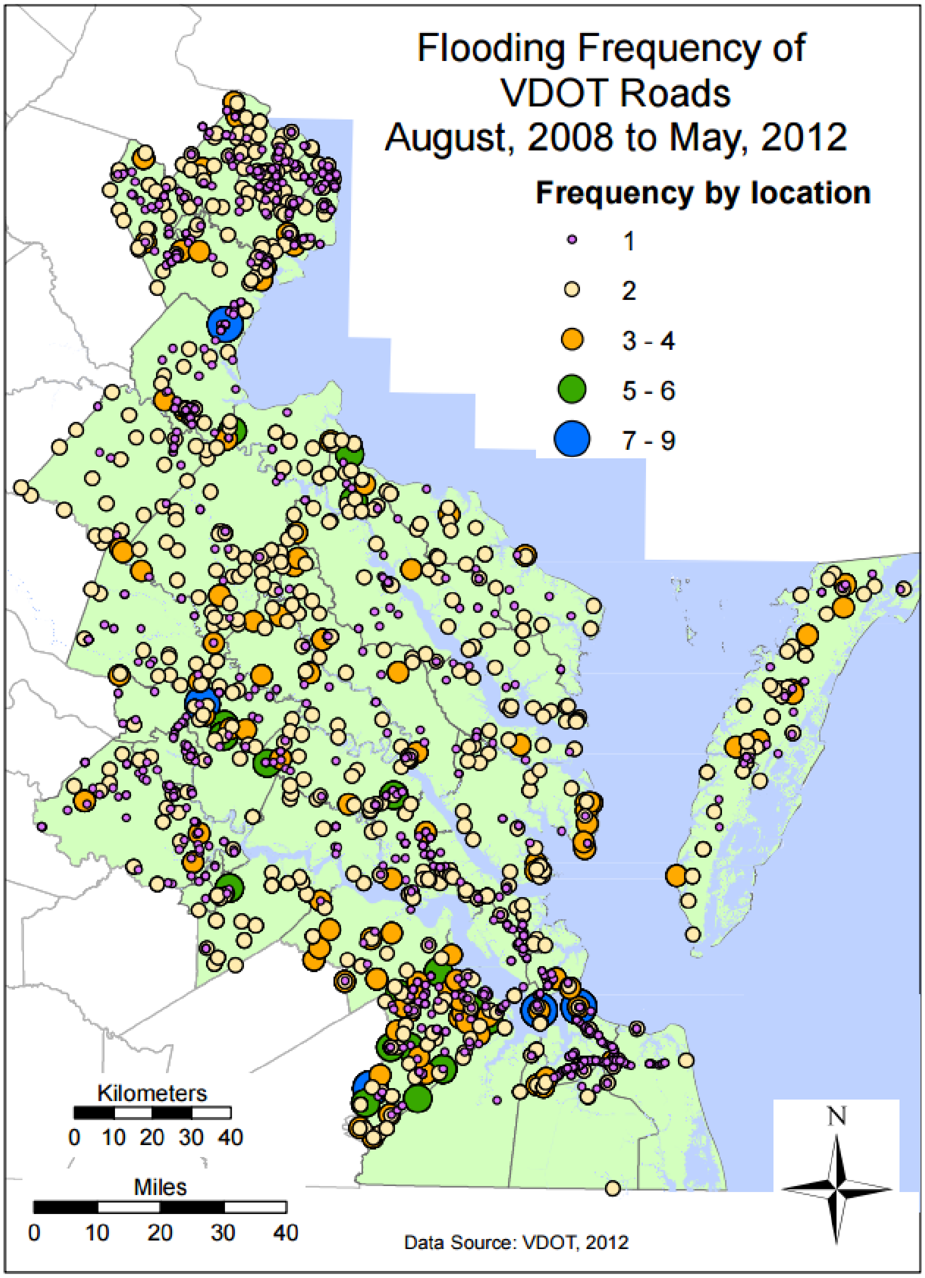

Figure 23. Flooding frequency of VDOT Roads (frequency summed over 2008-2012) (Source: VIMS (2013))

Sea Level Rise

In HR, the majority of the region's 2,900 square miles of development is located in low-lying land, no more than a few feet above sea level.[136] This places a number of transportation assets at risk to coastal flooding.

[136] HRTPO (2013b).

This section considers the historical and projected rate of sea level rise (SLR) for HR; illustrating the potential increase in flood threat to a number of transportation assets.

Global SLR. Globally, sea level has risen at a rate of 1.7±0.2mm (0.07 inches) per year from 1901 to 2010, accelerating to a rate of 3.2±0.4mm (0.13 inches) per year from 1993 to 2010 (see Figure 24).[137] Since 1992, sea level observations have improved through the use of satellite data.[138]

As shown in the figure below, NOAA suggests a risk-based scenario range of 0.2 meter (0.7 feet) to 2 meter (6.6 feet) relative to the year 1992.[139] Future rates are informed by a wide variety of analysis from semi-empirical methods to global climate modeling using various assumptions about future conditions. This results in a range of plausible future SLR by end of century, this range illustrates much of the uncertainty in the state of the science (e.g., rate of melting of glaciers and ice sheets) and regarding how global society may evolve (e.g., fossil-fuel use, population growth, etc.).

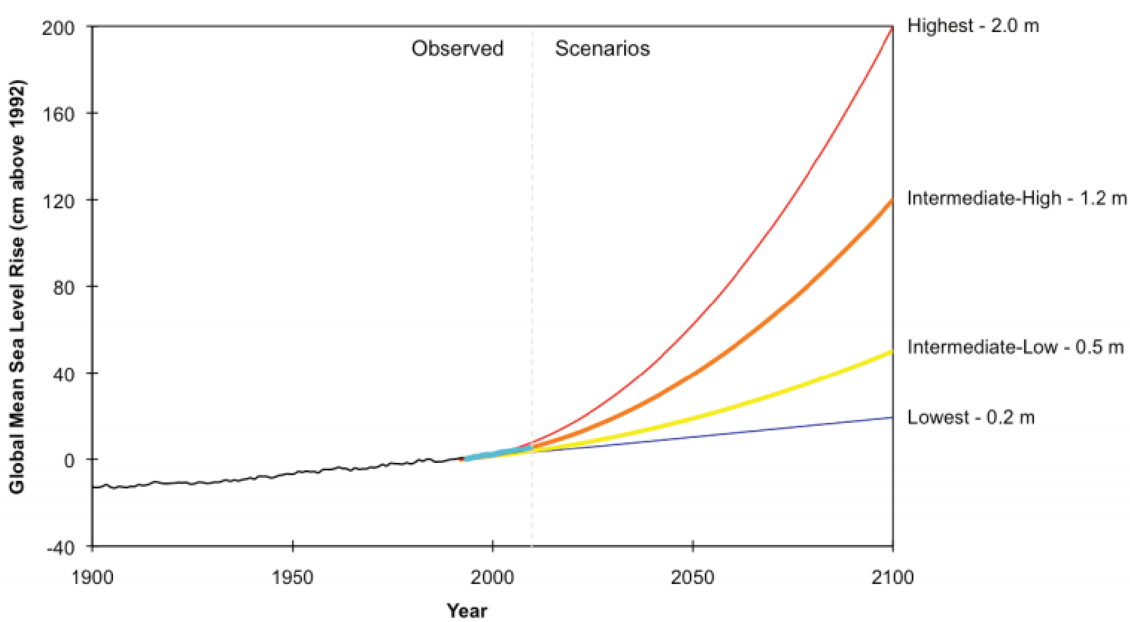

Figure 24. SLR projections, 1800 – 2100 (Source: NOAA (2012))

[137] Church, John A. et al. (2013).
[138] U.S. Global Change Research Program (2014).
[139] USGCRP (2014).

Local Sea Level Rise (SLR). The HR region has experienced local SLR (also termed relative SLR) greater than the global average. Local or relative SLR accounts for both global SLR such as caused by thermal expansion and melting of glacier and ice sheets and changes in local factors such as land subsidence, tidal patterns, and ocean density. For HR, the rate of local rise has been driven, in part, by land subsidence primarily in response to the disappearance of huge ice sheets which had caused a bulging in the Earth's crust around Virginia.[140, 141] In addition, the observed sinking along the coastline may also be exacerbated by groundwater withdrawal.[142] Another factor impacting SLR, in the HR region and beyond, is the measured slowing of the Gulf Stream current in response to changes in ocean currents.[143]

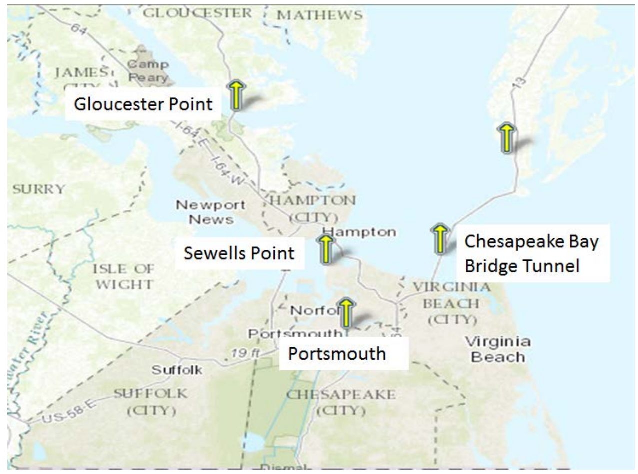

Figure 25. Sea level trends at NOAA tide gages within HR area (yellow area indicates a rise of 1 to 2 feet over the past century) (Source: NOAA Tides and Currents)

The HR region has a number of tide gages, all of which have measured an estimated increase of about 1 to 2 feet over the past century (see Figure 25), which is greater than the estimated historic global SLR of 0.6 feet (see Table 36). Though measured local SLR varies by tide gage in HR, the collective evidence suggests sea level is rising and at a greater rate than the global average. Given recurrent flooding is already an issue in HR, these findings would provide further support for considering ways to adapt to rising coastal waters.

Table 36. Mean sea level trends and estimated total rise for each of the HR NOAA tide gages (Source of data: NOAA Tides and Currents)

LOCATION	DATA RECORD	MEAN SEA LEVEL TREND (MM/YEAR) USING DATA RECORD	TOTAL RISE (CHANGE IN FEET OVER 100 YEARS)
GLOBAL	1901-2010	1.7 +/- 0.2 mm/year	0.6
SEWELLS POINT	1927-2015	4.59 +/- 0.23 mm/year	1.51
PORTSMOUTH	1935-1987	3.76 +/- 0.45 mm/year	1.23
CHESAPEAKE BAY BRIDGE TUNNEL*	1975-2015	5.93 +/- 0.77 mm/year	1.95
GLOUCESTER POINT	1950-2003	3.81 +/- 0.47 mm/year	1.25

**The mean sea level trend is higher than the other HR tide gages, likely in part because the trend is based on recent data during a time global sea level rise has accelerated.*

Considering the global SLR scenarios, a recent HRTPO/HRPDC (2016) report developed local sea level rise projections for Sewells Point relative to the year 1992 (see Figure 26). The choice of both local SLR scenario

[140] Virginia Institute of Marine Science (VIMS) (2013).
[141] Geologically, land subsidence is primarily driven by plate tectonics of post-glacial isostatic adjustment.
[142] Virginia Institute of Marine Science (VIMS) (2013).
[143] Although this topic is beyond the scope of this paper, reports on the Gulf Stream's slowing issue have been discussed in a variety of publications. See for example: https://www.odu.edu/news/2013/2/gulf_stream_sea_leve#.V6yVbU1TFLM.

and the future planning time horizon will directly affect which transportation assets are identified as exposed to future flooding. This is a critical decision point when considering an economic quantification analysis.

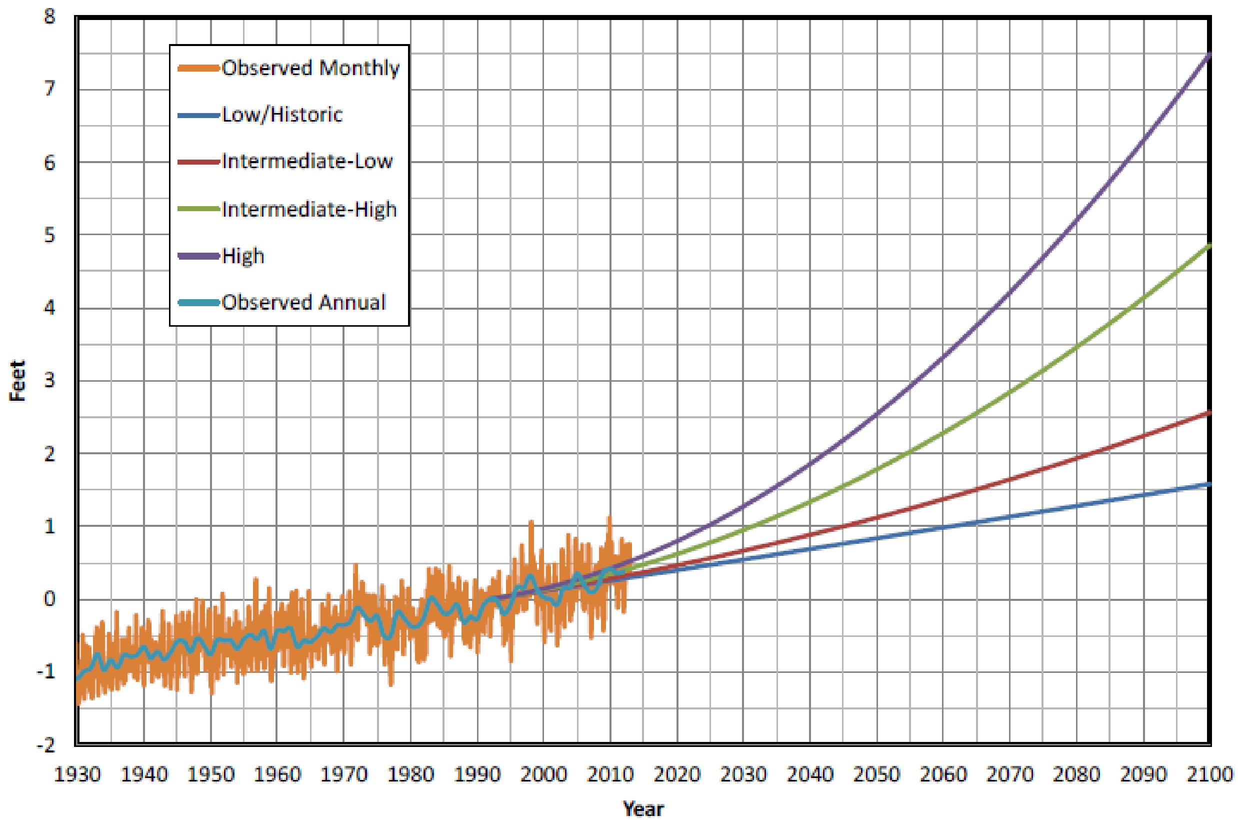

Figure 26. Observed and projected changes in sea level for Sewells Point tide gage (Source: HRTPO/HRPDC (2016))

NOAA's Sea Level Rise Viewer is a publically available web mapping tool that illustrates coastal flooding if sea level rise were to rise from 0 to 6 feet (at 1 foot increments) above average high tides (mean higher high water). Figure 27 shows coastal flooding in light blue shading within the Hampton Roads region under two feet of SLR. The bright green shading shows low-lying areas that will only flood if there is a means for water to flow into these areas (i.e., additional analysis is necessary to determine if these areas will, in fact, flood).

Figure 27. Coastal flooding at high tide for Hampton Roads with 2 feet SLR, inset Norfolk (Source: NOAA Sea Level Rise Viewer)

A number of low-lying jurisdictions within HR are considered vulnerable to SLR. Poquoson's elevation is below 10 feet along with much of Hampton and Norfolk.[144] Though Virginia Beach and Chesapeake are low-lying areas, much of the developed sections are at higher elevations. SLR not only contributes to coastal flooding but can cause erosion along coastal areas.

NOAA Sea Level Rise Viewer also considers future changes in shallow coastal flooding (see Figure 28). For the Sewells Point tide gage, NOAA Sea Level Rise Viewer suggests there are about 11 flood events per year (based

[144] VIMS (2013).

on 2007-2009 data) with flood duration totaling 2 days per year. Under a SLR of 0.5 meter (1.6 feet), NOAA estimates an increase to 345 flood events per year with flood duration totaling 53 days per year. This suggests there could be a flood event during the highest high tide almost every day of the year. For SLR of 1 meter (3.3 feet), the number of flood events per year could increase to 616 suggesting a flood event occurring almost every high tide (i.e., two high tides a day), with cumulative flood conditions lasting a total of 233 days per year. At this frequency, the land type would likely evolve into a wetland condition of saturated soils.

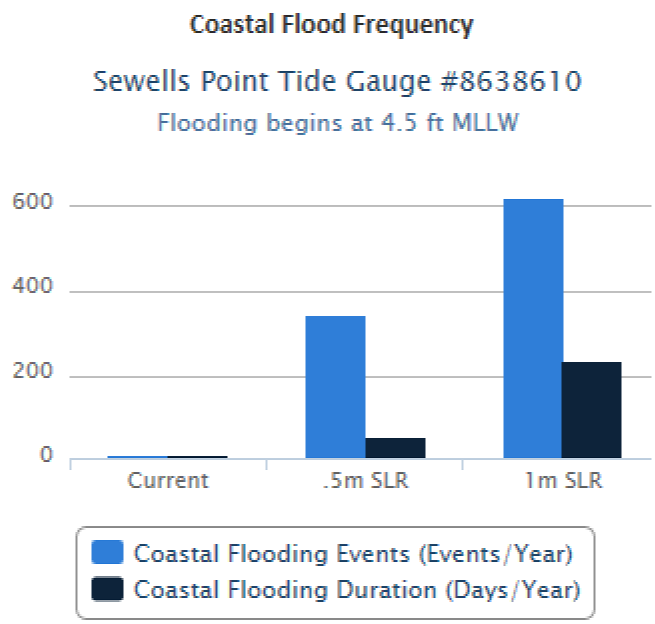

Figure 28. Flood frequency at Sewells point (Source: NOAA Sea Level Rise Viewer)

Storm surge

Coastal flooding is directly proportional to the storm surge, defined as the height of water above the predicted astronomical tide.[145] HR is vulnerable to storm surge from both tropical storms (e.g., hurricanes) and nor'easters. For the southeastern United States, recent research suggests that tropical storms represented 44 of the top 50 storm surge events between 1923 and 2008.[146] Within HR, the southeastern coastal area has experienced a greater number of coastal county hurricane strikes compared to the rest of HR (see Figure 29). These storms produce significant winds leading to damaging coastal flooding. The impacts of storm surge can be significant, and experts have emphasized that the destructive force of this phenomenon on built infrastructure has been underestimated,[147] as many focus solely on sea level rise. For example, the three primary impacts to the region's road network include: flooding of evacuation routes, increased hydraulic pressure on tunnels, and alteration to drainage capacity.[148] The severity of coastal flooding will worsen with

[145] NOAA (n.d.(a)).
[146] Grinstead et al. (2012).
[147]Botts et al. (2014).
[148] HRTPO (2013b).

sea level rise, prompting increased interests for developing adaptive measure to reduce the impacts of future flood events.[149]

One model routinely used by NOAA National Hurricane Center (NHC) and the climate community to simulate storm surge is NOAA National Weather Service's (NWS) Sea, Lake and Overland Surges for Hurricanes, or SLOSH model. SLOSH is a two-dimensional numerical model that estimates storm surge associated with historical, predicted, or hypothetical hurricanes by using storm parameters[150] to model the wind fields.[151] The SLOSH display program plays a useful role in helping emergency managers prepare for forecasted storms by illustrating forecasted storm surge.[152] Some climate vulnerability and/or screening assessments concerned with coastal inundation from storm surge have used SLOSH as an indicator of potential inundation exposure.[153] A drawback of using SLOSH is that the model does not consider: the impacts of waves on top of storm surge; tides on top of storm surge; normal river flow and rain flooding.[154]

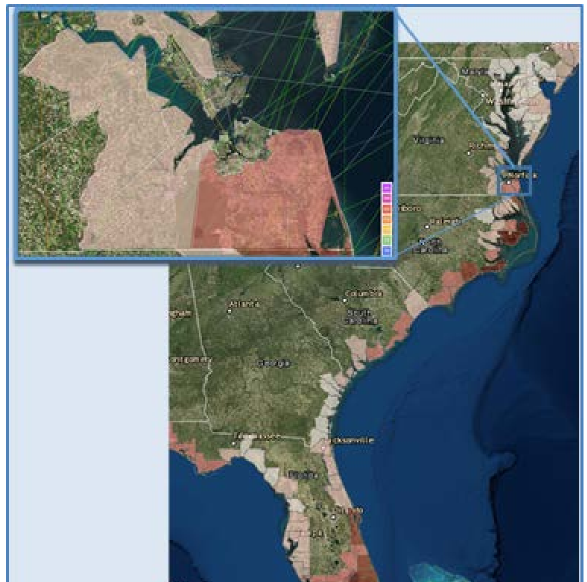

Figure 29. Hurricane strike frequency by county (Source: NOAA Historical Hurricane Track)

Recent analysis in HR has, instead, used ADCIRC modeling. ADCIRC can be simulated using either two or three dimensions and uses finite element analysis, allowing freedom in defining the latitude/longitude and elevation grid. This is particularly useful for storm surge analysis in that the storm can be modeled at a very fine resolution (e.g., 100 meters compared to 1km for SLOSH).[155] A drawback of ADCIRC is that it is computationally intensive, requires expensive elevation datasets using the remote sensing method Light Detection and Ranging (LiDAR),[156] and the results may not add significant value compared to SLOSH results, depending on the location and use.[157]

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[149] VIMS (2013).
[150] Storm parameters include atmosphere pressure, forward speed, and track. NOAA (n.d. (b)).
[151] The NHC study notes that the SLOSH model serves as the basis for a number of storm-surge models, and that regional emergency response (ER) managers have been using the model's data displayed in the SLOSH Display Program (SDP) to visualize forecasted storm surge. However the tool does not explicitly model the impacts of waves or tide on top of storm surge, nor does it account for normal river flow and rain flooding. See: http://www.nhc.noaa.gov/surge/slosh.php.
[152] VIMS (2013).
[153] Tate and Frazier (2013).
[154] VIMS (2013).
[155] Lin et. al. (2012).
[156] NOAA (2015).
[157] Lin et al. (2010).

Recent SLR/storm surge transportation vulnerability studies

Two recent assessments considered the impact of coastal flooding on HR:

- HRTPO (2016) analysis of HR roadway exposed to inundation under three scenarios to help inform the 2045 long-term transportation planning effort.
- Virginia Institute of Marine Science (VIMS) (2013) analysis that identified and illustrated coastal inundation overlaid with a number of layers of socioeconomic, natural environment, and built environment for SLR scenarios to help inform the 2043 long-term transportation planning effort.

These studies model HR's future exposure to coastal inundation. The VIMS (2013) analysis moves beyond just identifying exposure, with additional information provided below for completeness. Each is discussed below.

Quantifying Impacts of SLR

In Norfolk, there are three key relationships of vulnerability to flooding risks that make it difficult to fully quantify the impacts of SLR: a) indirect costs of recurrent flooding and uncompensated losses from business interruption; b) high poverty rates and wealth disparities that exacerbate the impacts; and c) lack of adequate private insurance protection that blurs the lines between public and private assets.

HRPTO (2016) study. With the growing recognition of the risks of SLR threatening Virginia coastal areas, HRTPO recently completed a study illustrating the areas and roadways within HR that may be submerged under 2 feet of relative SLR relative to the year 1992 (see Figure 30).[158] This study considered 2 feet as a possible level of SLR useful for informing the region's 2045 long-term transportation planning. In addition to SLR, the analysis considered storm surge inundation using the Region III Federal Emergency Management Agency (FEMA) ADCIRC modeling results for a 25-year storm surge and 50-year storm surge occurring "on top of" the relative SLR (i.e., the storm surge layers were "added" to the 2 foot SLR layer, with some additional processing to treat low elevation areas that are not tidally connected).[159]

[158] HRTPO (2016).

[159] The 25-year storm surge which has a 4 percent chance of occurring within any given year (based on historic records) is associated with water rise of 8.1 feet North American Vertical Datum (NAVD 1988) for Sewells Point. The 50-year storm surge which has a 2 percent chance of occurring within any given year is water rise above the surface of 8.8 feet NAVD.

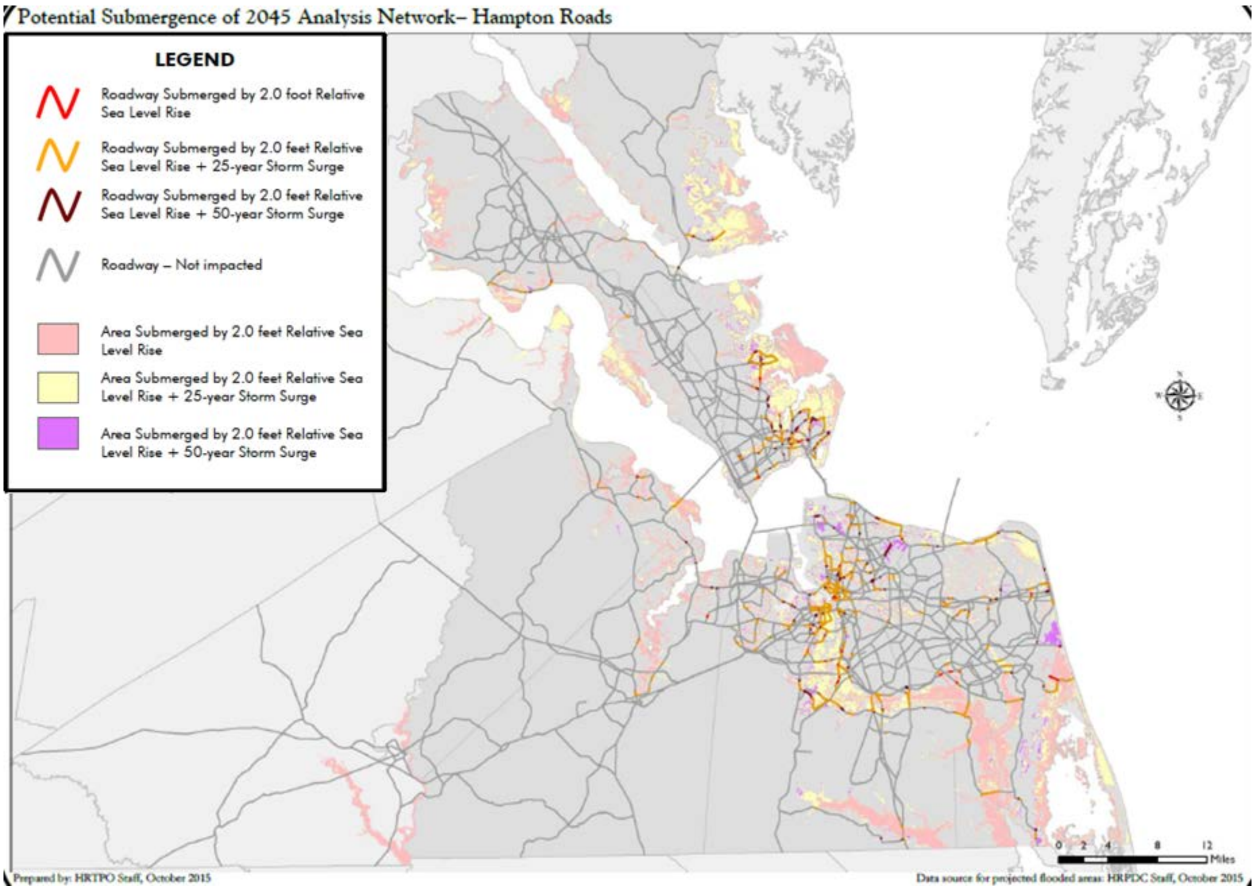


Figure 30. Hampton Roads with 2 feet SLR (Source: HRTPO (2016))

The HRTPO report suggests that existing roadways in Virginia Beach, Hampton, Norfolk, Newport News, and the Chesapeake could experience impacts if relative sea level were to rise 2 feet (relative to 1992 sea level). This is expanded to a number of additional jurisdictions when also considering the 2045 Analysis Network, with the greatest potential flooding of roadways occurring in Gloucester County and Poquoson (see Table 37). Considering storm surge with a 2-foot relative SLR introduces significant concern for many of the jurisdictions in HR, specifically Poquoson, Portsmouth, Norfolk, and Hampton where more than 10 percent of the roadways could be flooded under a 25-year storm surge. This increases quite a bit when the 2045 Analysis Network is included in the analysis – e.g., with a majority of roadways in Poquson being submerged under the 25-year storm surge and almost all roadways being submerged under the 50-year storm surge.

Table 37. Potential submergence of 2045 analysis network and existing roadways by Jurisdiction (HRTPO (2016))

Hampton Roads Jurisdiction	Total Centerline Miles	Scenario 1: 2 Ft Sea Level Rise		Scenario 2: 2 Ft Sea Level Rise + 25-Yr Storm Surge*		Scenario 3: 2 Ft Sea Level Rise + 50-Yr Storm Surge*	
		Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded	Centerline Miles Flooded	Percent Flooded
Chesapeake	1,213	3.1	0.3%	143.4	11.8%	177.3	14.6%
Gloucester County	653	15.7	2.4%	96.9	14.8%	106.1	16.2%
Hampton	698	3.6	0.5%	197.7	28.3%	247.5	35.5%
Isle of Wight County	680	0.4	0.1%	4.0	0.6%	4.5	0.7%
James City County	592	0.3	0.1%	8.6	1.5%	9.4	1.6%
Newport News	746	0.5	0.1%	15.8	2.1%	20.1	2.7%
Norfolk	948	5.2	0.5%	205.9	21.7%	272.9	28.8%
Poquoson	57	1.8	3.1%	48.4	84.5%	55.2	96.5%
Portsmouth	487	0.2	0.0%	114.3	23.5%	151.1	31.0%
Suffolk	854	0.2	0.0%	3.3	0.4%	4.3	0.5%
Virginia Beach	1,858	5.1	0.3%	129.6	7.0%	160.7	8.6%
Williamsburg	75	-	0.0%	0.1	0.1%	0.1	0.1%
York County	654	1.3	0.2%	45.0	6.9%	57.7	8.8%
	9,516	**37.5**	**0.4%**	**1,013.0**	**10.6%**	**1,267.0**	**13.3%**

** Centerline miles are cumulative for Scenarios 2 and 3. For example, Scenario 2 includes roadway segments from Scenarios 1 and 2. Scenario 3 includes roadway segments from Scenarios 1, 2, and 3.*

The HRTPO analysis is particularly helpful in understanding exposure to coastal inundation. This analysis can inform an economic quantification analysis by: (1) by drawing on the identification of which roadways may be submerged under these various future scenarios; and (2) using the series of GIS SLR and storm surge inundation layers to identify additional exposed transportation and sector-specific infrastructure.

VIMS (2013) study. An earlier study was conducted by the Virginia Institute of Marine Science (VIMS) to develop tools for estimating relative SLR risks to reduce some of the gaps when using climate data for long term project planning, including its absence in the HRTPO 2034 Long Range Transportation Plan (LRTP).[160] Using these tools, VIMS identified segments of the Virginia coastal areas (also known as the "Tidewater," this region includes HR) that are exposed to recurrent flooding of the roadways. This section serves as a brief summary of the tools and key discussion points of VIMS' *Recurrent Flooding Study for Tidewater Virginia* (2013) report.

[160] HRTPO (2012a).

For the Tidewater, VIMs estimates future SLR ranging from 1.6 to 7.5 feet between 1992 and 2100 based on four global SLR scenarios used by the recent U.S. National Climate Assessment. For planning purposes and drawing on these four global SLR scenarios, VIMS suggests that 1.5 feet of SLR is a reasonable estimate for the amount of SLR to occur in the Tidewater sometime between 2032 and 2065.

Example: Hurricane Isabel

Hurricane Isabel, initially a Category 5 storm that by the time of landfall in the region was reduced to a Category 1 storm, resulted in a storm surge of 5.13 feet above mean higher high water at the Sewells Point tide gauge, only slightly below the historical maximum flood of 5.26 feet above mean higher high water. Had the storm coincided with either a new moon or a full moon, higher maximum water levels could have occurred.

Source: NOAA (2004).

For simulating future storm coastal inundation between 2032 and 2065, VIMS suggests using a 3 foot storm surge on top of the 1.5 foot SLR to simulate vulnerability to future storm coastal inundation. This storm surge level was chosen as it is similar to that which has been experienced in the past. However, it is noted that storm surge can well exceed 3 feet. For example, Sewells Point tide gage recorded a 4.2 foot surge for Hurricane Irene in 2011 (also see textbox entitled "Example: Hurricane Isabel"). VIMS created a summary table of all coastal locations in coastal Virginia vulnerable to such a rise in water level. Table 39 shows the levels of vulnerability at several HR jurisdictions.[161]

Table 39. Top 7 HR Jurisdictions with vulnerability to a rise in water level of 4.5' (based on mean SLR of 1.5' and storm surge of 3') (Source: HRPTO (2013b))

HR JURISDICTIONS	TOTAL AREA (ACRES)	PROPORTION OF AREA WITH POTENTIAL TO FLOOD*	PROPORTION OF FLOOD-PRONE AREA DEVELOPED**	TOTAL FLOOD-PRONE DEVELOPED AREAS (ACRES)	CENTERLINE ROAD MILES PRONE TO FLOODING
NORFOLK	34,723	12%	60%	2,500	119
PORTSMOUTH	21,578	9%	57%	1,107	51
HAMPTON	33,171	15%	28%	1,393	50
CHESAPEAKE	217,011	11%	11%	2,626	103
VIRGINIA BEACH	145,465	26%	11%	4,160	289
POQUOSON	9,882	69%	11%	750	38
NEWPORT NEWS	44,297	13%	8%	461	15
TOTAL	**506,127**			**12,997**	**665**

**Proportion of location at risk of increasingly frequent flooding over the next 20-50 years;*
***Proportion of potentially flooded area currently classified as developed land;*

The Table above underscores the high level exposure in Norfolk to the risks of SLR and storm surge, compared to most other HR jurisdictions (with the possible exception of Virginia Beach and Chesapeake). The Table shows that while only 12 percent of Norfolk's total acres (4,167 acres) has the potential to flood, 60 percent of those acres in vulnerable area are developed parcels (a total of 2,500 acres and 119 miles of road), potentially

[161] The data, as reported by HRTPO, are based on the benchmarks derived from the VIMS (2013) report.

exposing many structures to flooding from SLR. This contrasts with Poquoson, where 69 percent of its acres have the potential to be flooded, but with only 11 percent of that land developed, only 750 developed acres are likely to be flooded.[162]

Exposure risks for Norfolk's highway infrastructure are also higher than the rest of the HR region. Table 39 below compares the exposure data from the HRPDC Phase III study, quantifying the portions of the region's roadway system at risk of exposure (focusing on mid-level estimate of rise of 1 meter above spring high tide). The table shows that about 7 percent of Norfolk's total road miles, and 9 percent of its interstate highway links are at risk of flooding from a 1-meter SLR, compared to 4.3 percent and 5.6 percent, respectively, for the HR region.

Table 39. Exposure to one meter of SLR above spring high tide in Hampton Roads and Norfolk (Source: HPRDC (2013))

ROAD INFRASTRUCTURE	HR REGION (ROAD MILES)			NORFOLK (ROAD MILES)		
	Total	Mid-Level Estimate	% of roadway system	Total	Mid-Level Estimate	% of roadway system
INTERSTATE	250	14	5.6	55	5	9.0
PRIMARY	1,460	50	3.4	153	9	5.9
SECONDARY	2,216	72	3.2	0	0	-
LOCAL OR PRIVATE	7,841	371	4.7	943	61	6.5
TOTAL ROAD-MILES	**11,767**	**507**	**4.3**	**1,150**	**76**	**6.6**

1-3-4 Extreme Heat Events

In the past, the Commonwealth of Virginia has experienced heat events severe enough to cause pavement buckling, such as in August of 2010.[163] This section summarizes our analysis of how heat events may change in the future using the Department of Transportation's Coupled Model Intercomparison Project 5 (CMIP5) Climate Data Processing Tool under two emission scenarios (moderately-low and a high) and ten statistically downscaled climate models.[164] Projections were developed for two future time slices, 2034-2054 and 2065-2084. The 2034-2054 future horizon was chosen to align with long-term planning documents and the 2065-2084 future horizon helps inform potential climate conditions that may be experienced within the asset lifetime for long-lived structures.

[162] The Wetlands Watch has observed that based on the 1.45ft/100yrs SLR assumption, if Sandy happened 100 years ago in 1912 it would've had a storm surge of only 2.64 feet above the benchmarked mean higher high water (MHHW) – i.e., the average of the higher of the two daily high tides over a 19-year cycle. Instead, the Sandy storm surge was 4.09ft above the MHHW. By 2050 this will be 5.59 feet. Source: Wetlands Watch (n.d.).

[163] Bogues (2010).

[164] This tool uses statistically downscaled daily temperature and precipitation data averaged over four 1/8 degree (12km) grid cells centered at Norfolk. The results of changes in heat event and heavy precipitation can provide a qualitative discussion of the direction of change for the HR area. The moderately-low emissions scenario was the relational concentration pathway to a global radiative forcing of 4.5 W/m^2 at the end of the century (i.e., RCP4.5) and the high emissions scenario leads to a global radiative forcing of 8.5 W/m^2 (RCP8.5). The statistically downscaled Reclamation data can be found here: http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

High temperatures can affect a number of transportation operations such as construction activities, as well as damage assets such as bridge joints and pavement. Future projections suggest that summertime extreme heat may become an increasing concern in the future. By mid-century, there may be between 17 and 21 days per year above 95°F (see Figure 31). Later in the century, that number could increase to as many as 48 days per year. The duration of hot days may also be in slightly longer stretches, increasing the possibility of heat events. By mid-century, hot temperatures may last 5 to 7 consecutive days per year, compared to the baseline of 3 consecutive days per year. Later in the century, hot temperatures may last one to two weeks.

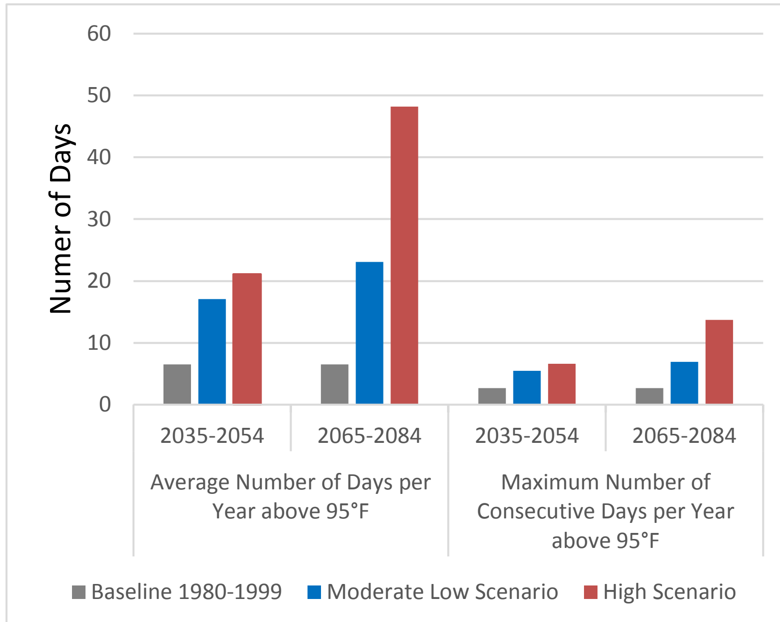


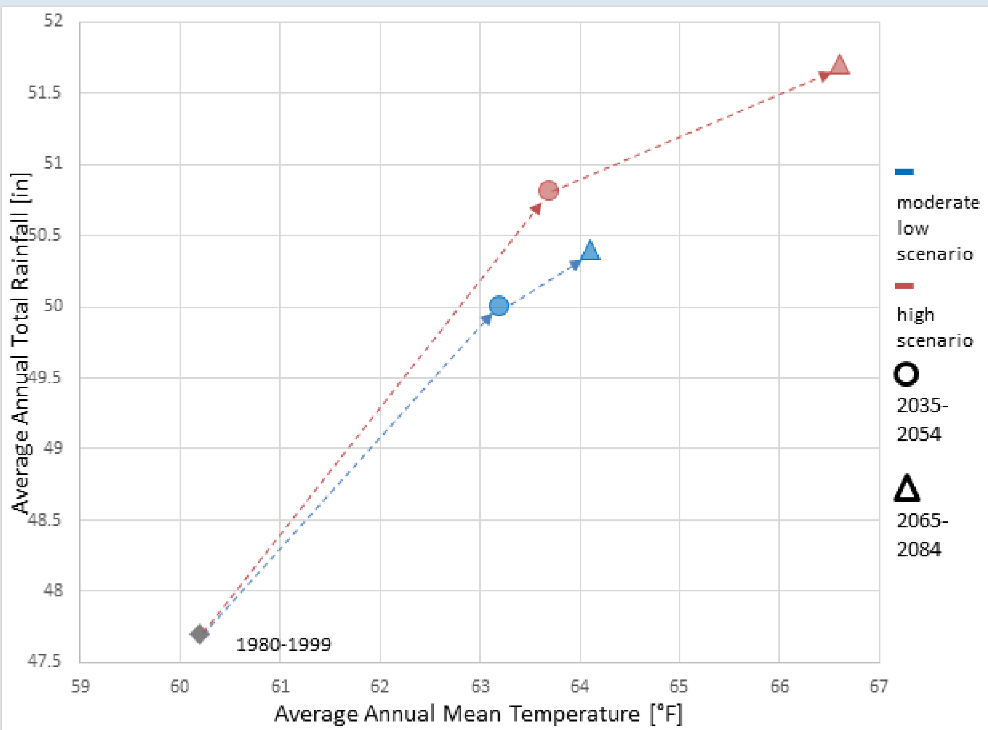
Figure 31. Average number and maximum consecutive number of hot days per year above 95°F

In addition, the highest 4-day average summer high temperature is projected to increase from 95°F to between 98.5°F and 99.3°F by mid-century and to between 99.6°F to 102.9°F in the latter half of the century. Similar increases are projected for the highest 7-day average summer high temperature. These temperature thresholds may be relevant to transportation engineers and planners.

Future Change in Annual Precipitation and Temperature

Under both emissions scenarios (moderately-low and high), Norfolk is expected to be warmer and wetter in the 21st Century. Over the next few decades, annual average temperatures may rise between 3.0°F ±0.5°F and 3.5°F ±0.5°F, with precipitation increasing by 5 percent to 6 percent. In the latter half of this century, temperatures may rise between 3.9°F±0.7°F and 6.4°F ±0.9°F, with precipitation increasing by 6 percent to 8 percent. The largest seasonal increase in precipitation is projected to occur during the winter months (approximately 10 percent increase) regardless of scenario or future time horizon. These changes may not cause dramatic impacts on transportation assets such as a flood event, but these changes may impact transportation planning and the overall integrity of assets through reactionary stressor changes in ecology, vegetation, and soil moisture.

Historic and Projected Changes in Annual Temperature and Precipitation



1-3-5 Heavy Precipitation Events

HR has experienced a number of heavy precipitation events over the past few decades that have led to FEMA disaster declarations and significant flooding. From our analysis using the USDOT CMIP Processing Tool, Figure 32 shows the average number of "very heavy" precipitation events each year.[165] By mid-century, the projections suggest two additional "very heavy" precipitation events compared to the historical record of 11 events per year. Towards the latter half of the century, there may be two to four more events per year. While this is only about a 20 percent increase, it may lead to more flooding, especially when coupled with SLR. In addition, the largest seasonal 3-day precipitation event is projected to increase by about 50 percent during the winter months[166] regardless of the scenario and future time horizon. This is consistent with future projections for North America.

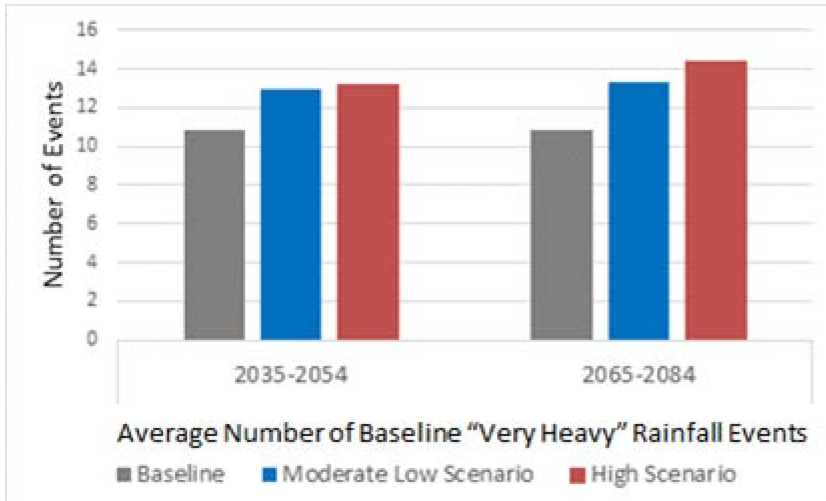


Figure 32. Average number of "very heavy" rainfall events per year

In North America, climate science projections indicate that *likely* outcomes of changing future conditions are increases in precipitation event magnitudes (e.g., depths or intensities), durations, and occurrences (including separate events occurring within very close intervals, i.e., days).[167] As a result, flooding will constitute an increasing concern for transportation assets.

Several current products that identify locations prone to varying levels of flood risk, such as the Federal Emergency Management Agency's (FEMA) Flood Insurance Rate Maps (FIRMs), allow the consideration of impacts to transportation assets and services. To illustrate, FIRMs assist identification of transportation assets affected from floods associated with the 100-year event (aka, base flood or A-zone) or 500-year (X-zones) events and associated floodplains. Given the proper analyses, they may also provide some rough qualification of future projected flood extents and floodplains. For example, as a result of climate change, increased precipitation depths change sufficiently such that the flooding associated with the current 100-year event may only coincide with the future 85-year event. In such a hypothetical example, logically this infers an increase in the precipitation depth associated with the 100-year exceedance frequency. As a result, the future 100-year event would produce an extent of flooding that exceeds the current 100-year FIRM area (but likely not to extend beyond the 500-year floodplain extent). Therefore, at a planning stage, practitioner may be able to then ascertain that those transportation assets

[165] A "very heavy" precipitation event is one that is at or above the 95th percentile of precipitation in the baseline period.
[166] Winter months are defined as December, January, and February.
[167] IPCC (2013).

within the boundaries of the 100-year and 500-year FIRM areas represent those likely associated or affected by future climate conditions.

DOT's quantification study augments the science-based implementation of the Federal Flood Risk Management Standard (FFRMS), based on the authority of Executive Order (EO) 11988, as amended by EO 13690. 80 FR 6424 (2/04/14). The FFRMS, applicable to federally-funded actions (e.g., projects), calls for agencies to use a higher vertical flood elevation and corresponding horizontal floodplain than the base flood for projects to address current and future flood risk, and avoids actions that have negative economic consequences. The FFRMS provides each federal agency some latitude in determining what approach to use to establish the vertical extent of the FFRMS floodplain (i.e., CISA, Freeboard, or 500-year). However, in the case of multiple agency involvement in an action, Step 1 of "Guidelines for Implementing EO 11988 and EO 13690" (Guidelines) (October 8, 2015) encourages early coordination of such agencies to ensure consistent approaches in floodplain determinations. These floodplain determinations necessarily include both the vertical extents and the horizontal extent of the FFRMS floodplain. Therefore, this augmentation study recommends producing a "memorandum of agreement" (or other similar agreement) from Federal agencies that documents agreed upon approaches, processes, and mechanisms for ensuring such consistency of FFRMS floodplain extents and delineations.[168]

1-4 – DATA ON CLIMATE-RELATED IMPACTS ON TRANSPORTATION INFRASTRUCTURE

The HR region has experienced a number of threats that can cause property loss and fatalities. This section identifies past extreme weather events that have been particularly costly for HR and the associated impacts on transportation and the community. In addition, this section presents recent HR studies that have quantified losses due to the impacts of SLR and flooding on transportation.

1-4-1 Impacts to the Transportation System by Past Extreme Weather Events

We used the NOAA's Storm Event Database[169] to identify past storm events that caused enough damage to significantly impact the region (defined in this report as events causing $100,000 or more in property damage). Identifying the impacts associated with past storms can act as a surrogate for understanding sensitivities within the region. This section uses NOAA's Storm Event Database, Spatial Hazard Events and Losses Database for the U.S. (SHELDUS), and FEMA Disaster Declarations Summary to identify recent storms that caused significant economic damages to the region. For these storms, media reports were mined to describe impacts on the transportation system, utilities, environment, and property. This provides insight regarding existing sensitivities to specific types of events.

[168] A discussion of design matters and determinations regarding encroachments to flood plains under 23 CFR parts 625 and 650 is beyond the scope of this study.
[169] NOAA (n.d. (c)),

NOAA's Storm Event Database includes extreme weather events that meet one or more of the following criteria:

- Causes mortality, injuries, notable property damage and/or disruption to commerce (i.e., may be significant event affecting the reliability and integrity of the transportation network);
- Unusual event for a given location that generates media attention (i.e., assets may not be designed/built with these unusual exposures in mind);
- Combination of a significant meteorological event with another event (i.e., assets may be exposed to synergistic impacts).

From 1997 to 2015, the database includes property damages associated with hurricanes, tropical storms, coastal flooding, thunderstorms (lightning and winds), hail, high winds, strong winds, and tornadoes. Prior to 1997 the database is limited to thunderstorms (high wind), tornadoes, and hail. It should be noted that the storm type identifier for a particular storm may not be attributed to the actual weather event type but instead may identify the event's component causing the damage (e.g., heavy wind may in fact be from a nor'easter or tropical storm; a coastal flood may be associated with a tropical storm).

EVENT TYPE	ROUGH ESTIMATE OF PROPERTY DAMAGE (1997 TO 2015)
HURRICANES/TROPICAL STORMS	$585,554,000
FLOODING	$139,111,800
HAIL EVENTS	$17,123,000
HIGH/STRONG WINDS	$5,265,000
TORNADOES	$49,687,000
THUNDERSTORMS	$4,674,000
WINTER/ICE STORMS	$20,120,000
TOTAL	**$821,534,800**

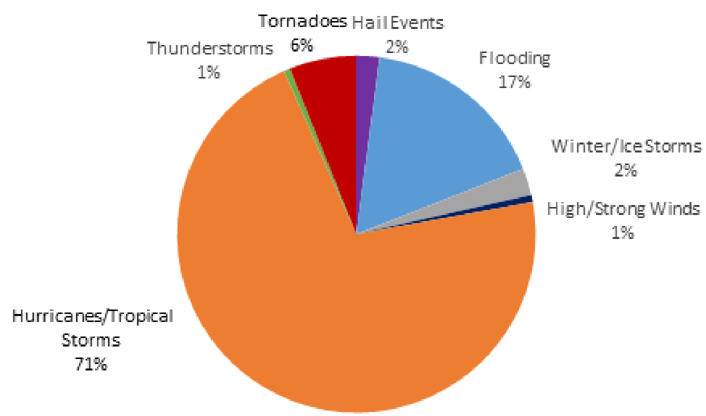


Figure 33. Rough estimate of property damage by storm event type for HR from 1997 to 2012 (nominal values are used so this is a rough estimate) (Source: based on data from NOAA Storm Events Database)

As shown in Figure 33 and 34, hurricane and tropical storms are responsible for the greatest property damage to HR over the past 19 years, followed by coastal flooding. These property damage estimates are rather rough estimates as the NOAA Storm Event Database monetizes property damage of an event by summing across all counties that report this event per the criteria listed above (hence, it's an overestimate as it's not disaggregated to property damages specific to a specific county) and the Database does not adjust property damage amounts to the current year (i.e., doesn't take into account inflation, etc.). If more accurate estimates are needed, a fee-for-service database, The Spatial Hazard Events and Losses Database for the U.S., or SHELDUS, is available that uses the data in the NOAA Storm Event Database to provide county-level disaggregated costs (by dividing the event costs equally across counties, which may underestimate or overestimate the actual costs to that county) and accounts for inflation. In addition, SHELDUS is helpful for trend analysis as it includes additional sources of information to provide property damages associated with extreme weather events from 1960 to 2014.

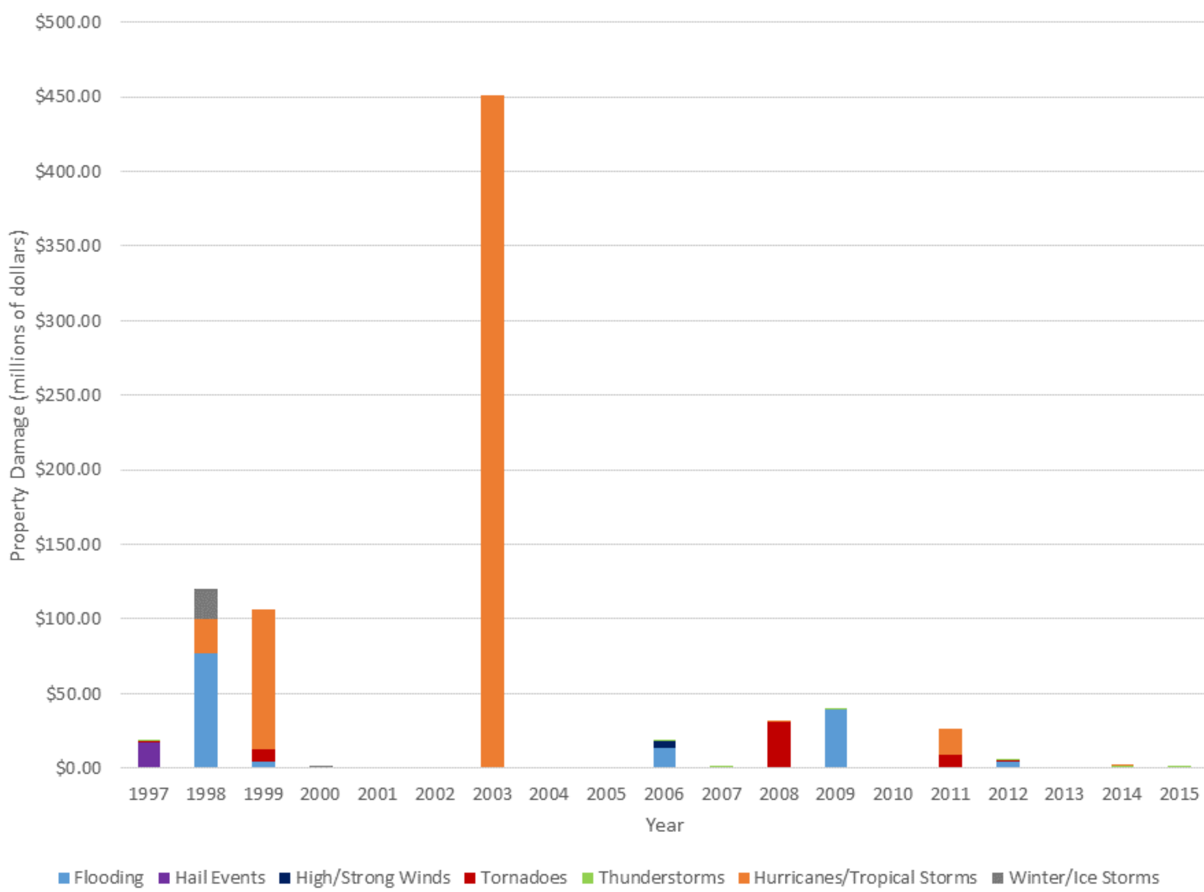


Figure 34. NOAA data on estimated property damage from by storm event type in HR (Source: based on data from NOAA Storm Events Database)

A few additional points were gleaned through inspection of SHELDUS property damage data incurred in Norfolk over that 54-year period: (1) most severe property damage was associated with a handful of relatively infrequent events of large magnitude (30 of the 229 storm events reported more than $100,000 in property damage; 12 of the 229 storm events reported more than $1,000,000 in property damage); and (2) flooding caused by heavy precipitation was as or more costly than flooding caused by a hurricane or coastal surge.

From this analysis, a number of storm events were identified that affected both HR and Norfolk (see Table 40).

Table 40. Storm events that have affected Norfolk and caused at least property damage of at least $100,000 (Source: data from NOAA Storm Events Database)

EVENT	DATE	DAMAGES*
HURRICANE SANDY	10/28/2012	$500,000
HURRICANE IRENE	8/27/2011	$4,500,000
NOR'EASTER	11/12/2009	$18,000,000
SUPERCELLS	4/28/2008	$100,000
NOR'EASTER	11/22/2006	$100,000
TROPICAL DEPRESSION ERNESTO	9/1/2006	$1,000,000
HURRICANE ISABEL	9/18/2003	$10,000,000

**Actual dollars when the event occurred.*

In addition, FEMA Disaster Declarations Summary was reviewed to determine past storm events.[170] Counties in HR have declared between 8 to 17 disaster declarations, while cities in HR have declared between 8 to 15 disaster declarations since 1953 (see Figure 35). These numbers may overestimate the total number of storm events as some of these disaster declarations were multiple declarations in the same location for the same storm event, so consider the results somewhat qualitatively.

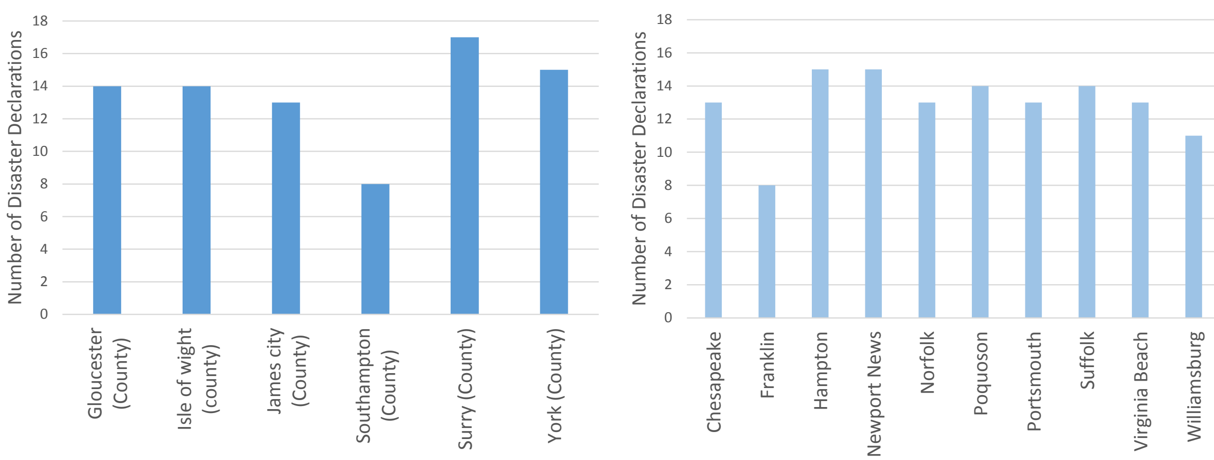


Figure 35. Disaster declarations for the counties and cities in HR since 1953 (Source: data from FEMA Disaster Declarations Summary)

A majority of these extreme weather events were hurricanes/tropical storms followed by winter events (see Table 41). These extreme weather events – notably – did not include heat events or drought. This may suggest that either the HR area has simply not experienced significant heat events or droughts *OR* these events do not cause enough damage to warrant a disaster declaration. Most of these extreme weather events are also consistent with the storms identified using the NOAA Storm Events Database as causing significant damage.

[170] FEMA (2016).

Table 41. Extreme weather that led to FEMA disaster declarations for Hampton Roads (Source: data from FEMA Disaster Declarations Summary; Note date provided in parenthesis is the declaration date not the storm date)

HURRICANES/TROPICAL STORMS	WINTER WEATHER
HURRICANE SANDY (11/3/2012)	Severe storm/flooding (12/9/2009)
HURRICANE IRENE (9/3/2011)	Severe winter storm (2/28/2000)
TROPICAL DEPRESSION ERNESTO (9/22/2006)	Blizzard of 1996 (1/13/1996)
HURRICANE KATRINA (9/19/2005)	Severe Ice Storms (3/10/1994)
HURRICANE ISABEL (9/18/2003)	Severe winter storm (3/25/1993)
HURRICANE FLOYD (9/18/1999)	Severe storms and flooding (11/9/1985)
HURRICANE BONNIE (9/4/1998)	Ice conditions (1/26/1977)
HURRICANE FRAN (9/6/1996)	
TROPICAL STORM AGNES (6/23/1972)	

This collection of information is useful to pull out events that had significant impact in the area and investigate potential impacts on the transportation network. Of those storms that are directly linked to the climate stressors considered in this report (e.g., SLR, storm surge, heavy precipitation), there are 8 storm events that were responsible for substantial damage. A targeted literature review of media records was conducted to identify the storm and present recorded impacts on the transportation system (see Table 42).[171]

Table 42. The weather-related stressors and impacts by historic storm event for HR and Norfolk (Sources: sources used in the table are marked with an asterisk in Appendix B)

EVENT	DATE	STRESSORS	IMPACT
HURRICANE SANDY*	10/28/2012	Hampton Roads: ▪ Very heavy rainfall ▪ Storm surge (high tide about 4 ft above MHHW) ▪ Sustained winds 30-35 mph ▪ Winds at 41 mph recorded at Langley ▪ Flooding of low lying areas of Poquoson, Hampton and Gloucester (high tide was about four feet above normal)	▪ Downed trees ▪ Power outages ▪ Significant flooding ▪ No major incidents or accidents related to the bad weather ▪ All local bridges and tunnels remained open to traffic except unusually high tides closed one lane in each direction on the James River Bridge
		Norfolk: ▪ High tide and powerful surf ▪ 6.85 ft above MHHW at Sewells Point ▪ 5.68 in of rain at ORF through 8 am 10/30	▪ Significant flooding ▪ Closed Midtown tunnel, evacuated some areas ▪ 61 people in shelters

[171] Additional federal funding programs that may provide damage information related to these storms include the FHWA Emergency Relief Program, FTA Emergency Relief Program, Airport and Airway Trust Fund, and special appropriations to the Federal Railroad Administration and the National Railroad Passenger Corporation. (USDOT FHWA (2014b)).

EVENT	DATE	STRESSORS	IMPACT
HURRICANE IRENE*	8/27/2011	Hampton Roads: ▪ Many jurisdictions received high rainfall totals ranging from 6.23 inches (Newport News) to 11.04 inches (Suffolk) ▪ Winds reached 65 miles per hour (mph). ▪ Storm surge 3.5 to 4.5 ft	▪ Debris and downed trees in Suffolk ▪ Death in Newport News because of downed tree ▪ Flooding
		Norfolk: ▪ 7.5 ft at Sewells Point (weather service) 7.63 ft at Sewells Point (Norfolk) ▪ 4.53 in of rain	▪ Downed trees
NOR'EASTER*	11/12/2009	Hampton Roads: ▪ Storm tide 8.59 ft above MLLW; 6.86 ft above MLLW at Coast Guard pier on York River[172] ▪ Max sustained winds 42 mph ▪ Rainfall: 11.92 in Chesapeake; 11.86 in Hampton; 10.58 in Suffolk; 10.58 in Langley; 9.76 in Newport News; 8.66 in Portsmouth; 8.47 in Norfolk	▪ Property damage: ; $450,000+ Portsmouth; $3.4 million Virginia Beach ▪ Downed trees, debris ▪ Eroded Cape Henry beaches
		Norfolk: ▪ 7.75 ft high water mark Sewells Point ▪ 8.47 in rain	▪ Flooding ▪ Over $25 million in property damage
SUPERCELLS	4/28/2008	Hampton Roads: ▪ 11 tornadoes ▪ 3 were EF-0, 7 were EF-1, one was EF-3 ▪ Winds possibly above 135 mph ▪ Travel velocities from 15 m/s to 23 m/s for EF-3 tornado	▪ 200 people injured ▪ Debris, blown-out windows ▪ 12+ homes destroyed, several hundred damaged ▪ $20 million in property damage
NOR'EASTER	11/22/2006	Hampton Roads: ▪ 50-60 mph winds ▪ 6.8 ft high tide at Sewells Point	▪ Flooded streets, Midtown tunnel closed[11] ▪ Power outages affecting 2,200 customers in Southeast VA ▪ Downed branches and trees
TROPICAL STROM ERNESTO*	9/1/2006	Hampton Roads: ▪ Strong winds, heavy rains, storm surge ▪ 5-8 in of rain ▪ Gusts of 60-70 mph ▪ Tides 4-5 ft above normal ▪ 6+ in of rain	▪ Newport News, Poquoson, Gloucester, Isle of Wight, James City, Surry, and Sussex declared major disaster areas ▪ Flooding ▪ Damaged homes, piers, boats, marinas ▪ 200,000 lost power

[172] Mean Lower Low Water (MLLW) is the average of the lower of the two daily low tides over a 19-year cycle.

HURRICANE ISABEL*	9/18/2003	HAMPTON ROADS: ▪ 61 MPH WINDS AT CBBT ▪ 7.9 FT ABOVE MLLW AT SEWELLS POINT, 5 FT STORM SURGE[15], 5.13 FT ABOVE MHHW AT SEWELLS ▪ 5.62 FT MAX STORM SURGE ▪ SECOND HIGHEST ABSOLUTE WATER LEVEL RECORDED AT SEWELLS POINT ▪ 60 KT SUSTAINED WINDS AT GLOUCESTER POINT ▪ 50 KT SUSTAINED WINDS AT NORFOLK NAS ▪ 5-6 FT STORM SURGE IN HR ▪ CBBT 52 KT SUSTAINED WINDS, 4.78 FT STORM SURGE, 7.53 FT STORM TIDE ▪ 2.5 IN RAIN AT ORF, 4.21 IN AT NAS ▪ 60-70 MPH WINDS	▪ BEACH EROSION ▪ TREES AND POWER LINES DOWN ▪ POWER OUTAGES ▪ UPROOTED TREES ▪ FLOODING ▪ MIDTOWN TUNNEL CLOSED

**Indicates this storm prompted a disaster declaration in at least one city and/or county in HR.*

In addition to this information, VDOT's Safety, Security & Emergency Management Division provided emergency transportation costs related to Hurricane Irene for the Commonwealth of Virginia. This information is a record of project costs and type funded for cleanup and repair. The majority of funds were spent on cleanup/debris (93 percent) (see Table 43). Emergency protective measures, repairing roadway damage, and facilities (e.g., fencing) represent the remaining funds (7 percent). This historical information is useful for including emergency management transportation costs associated with potential events. This information can also be collected for additional storms to formulate high-order emergency transportation costs across storm types. Additional storm-related transportation project costs may be available by reviewing FEMA and FHWA reimbursement records.

Table 43. Transportation project costs for Virginia in the wake of Hurricane Irene (Source: VDOT data)

TYPE	# OF PROJECTS	SUM OF COSTS	% OF TOTAL COSTS
CLEANUP/DEBRIS	62	$17,184,233	93.3%
EMERGENCY PROTECTIVE MEASURES	32	$869,073	4.7%
ROADWAY DAMAGE	22	$338,613	1.8%
FACILITIES	7	$35,842	0.2%
TOTAL	**123**	**$18,427,761**	

1-4-2 Recent Studies Quantifying Costs of Climate-Related Impacts

There are three recent studies in HR that quantify losses associated with SLR and storm surge. These studies consider direct losses due to SLR and flooding across multiple sectors. From the transportation perspective, some of the direct losses estimated by these studies may help inform estimates of potential indirect losses when looking through the lens of indirect impacts associated with the flooding of transportation

As noted in the discussion of economic impact analysis (EIA), estimates of how much adverse climate-related events would cost the economy depend on the share of the specific industry sector—finance, manufacturing, transportation, etc. in the region—in terms of their contribution to the region's GDP. Regional economic impact studies provide a baseline assessment capability for these impacts.

HRPDC Roadways and Property Loss due to SLR

The HRPDC Phase III study of SLR risks in HR has produced an extensive report on the exposure of the HR jurisdictions and their roadway network to SLR risks, and has developed baseline data on the potential economic losses in the region. [173] Appendix D describes the methodology HRPDC used to estimates these values.

Two indicators were used to represent the value of impacts: number of parcels affected by SLR and the total dollar value of improvements on the parcel. Parcels that had any portion included in the vulnerable zone were measured as "intersection" metrics. Parcels for which the centroid (weighted middle of the polygon) was within the vulnerable zone were considered as the inventory of properties that would be significantly impacted by 1-meter of SLR above spring high tide, under all three risk scenarios for exposure—low, middle, and high – to account for uncertainty associated with the elevation data.[174]

The HRPDC has produced cost estimates for potential damages from exposure to SLR risks for HR and Norfolk. Exposure data for the transportation network include an assessment of bridge condition described previously in this report. Because the exposure models do not incorporate the potential risk reduction benefits from any current or planned shoreline protection and flooding mitigation improvements, the exposure risk estimates should be considered baseline estimates for the *"Do Nothing Scenario"* that assumes no improvements in the baseline risks.

The analysis revealed localities that are particularly vulnerable to future SLR, including: Chesapeake, Gloucester County, Hampton, Norfolk, Poquoson, Portsmouth, Virginia Beach, and York County. Within HR, this study found that approximately between 1.4 to 7.5 percent of total roadway miles are exposed to 1 meter of SLR above spring tide (see Table 44). There is a greater potential of total roadways being exposed under the high scenario for Norfolk where between 1.3 to 11.2 percent of total roadway miles may be exposed (see Table 45). The study provides a large collection of inundation maps which illustrates an additional component when considering long-term planning to reduce or mitigate transportation vulnerabilities. If roadways are servicing specific neighborhoods that are particularly vulnerable to SLR – will long-term planning evolve in such a way as to reduce the need for maintaining specific roadways (i.e., since the neighborhood it's servicing has migrated to drier ground) or introduce shoreline protections that remove the potential exposure all

[173] HRPDC (2012).

[174] The scenarios consider varying rates of sea level from the current rate ("low scenario") to 0.5 meters of rise adjusted to reflect historic trends at local tide gages ("medium scenario") and 1.5 meters of rise adjusted to reflect historic trends at local tide gages ("high scenario").

together. For example, Norfolk may be greatly affected by SLR. Currently, the SHELDUS records suggested $116M of property damage from the flooding events in Norfolk for the 1960-2014 period. Under future SLR conditions, the HRPDC Phase III study identified over $350M of real estate in Norfolk where the centroid of the property was in the one-meter sea-level rise flood zone, and over $1.7B of real estate in Norfolk where there is at least some portion of the property in the one-meter sea-level rise flood zone.[175] If future planning builds in protection mechanisms for these properties, this may also reduce roadway flooding.

Table 44. Exposure to one meter SLR above spring high tide in Hampton Roads (Source: HRPDC (2012))

EXPOSURE	TOTAL	LOW RISK ESTIMATE	MIDDLE RISK ESTIMATE	HIGH RISK ESTIMATE
LAND AREA (SQ. MILE)	2,948	171	238	311
POPULATION	1,666,310	59,59	112,794	176,124
HOUSING UNITS	677,49	24,436	45,791	71,548
# PARCELS (INTERSECTION)	605,284	39,564	61,254	84,780
# PARCELS (CENTROID)	605,284	16,000	35,654	58,651
IMPROVEMENT VALUE (INTERSECTION)	$128,305,696,321	$20,328,915,919	$26,161,421,399	$30,833,003,959
IMPROVEMENT VALUE (CENTROID)	$128,305,696,321	$4,142,308,080	$8,766,633,550	$13,410,140,979
TOTAL ROAD MILES	**11,676**	**161.5**	**507**	**877**
INTERSTATE	**250**	**5.7**	**14**	**18**
PRIMARY ROADS	**1460**	**17**	**50**	**77**
SECONDARY ROADS	**2216**	**24**	**72**	**98**
LOCAL/PRIVATE ROADS	**7840**	**114.7**	**371**	**684**
# BUSINESSES	57,579	575	2026	3,659
# EMPLOYEES	719,835	5,237	25,088	50,869
TOTAL VALUE OF PARCEL (INTERSECTION)	$215,436,678,988	$38,892,731,860	$48,067,888,230	$56,306,819,672
TOTAL VALUE PARCEL (CENTROID)	$215,436,678,988	$8,513,744,141	$16,466,833,462	$25,104,125,807

[175] HRPDC considers these as conservative estimates that take into account uncertainties associated with the accuracy of the elevation data. It should be noted that the SHELDUS data are retrospective estimates based on actual damages, while the HRPDC damage estimates relate to the value of the assets in the flood zone at risk of potential damage.

Table 45. Exposure to one meter SLR above spring high tide in Norfolk (Source: HRPDC (2012))

EXPOSURE	TOTAL	LOW ESTIMATE	MIDDLE ESTIMATE	HIGH ESTIMATE
LAND AREA (SQ. MILE)	56	3.1	6.5	9.2
POPULATION	242,803	9841	25,715	36,134
HOUSING UNITS	95,018	3502	8,955	12,896
# PARCELS (INTERSECTION)	65,979	4,555	8,251	11,567
# PARCELS (CENTROID)	65,979	1,757	4,968	8,204
IMPROVEMENT VALUE (INTERSECTION)	$13,494,681,500	$1,703,705,500	$3,207,444,200	$3,917,995,600
IMPROVEMENT VALUE (CENTROID)	$13,494,681,500	$350,808,300	$1,325,957,300	$2,234,621,300
TOTAL ROAD MILES	**1,150**	**15**	**76**	**129**
INTERSTATE	**55**	**1.7**	**5**	**7**
PRIMARY ROADS	**152**	**1.0**	**9**	**13**
SECONDARY ROADS	**0.0**	**0.0**	**0.0**	**0.0**
LOCAL/PRIVATE ROADS	**943**	**12**	**61**	**109**
# BUSINESSES	9,118	111	532	946
# EMPLOYEES	136,292	1,924	9,818	15,014
TOTAL VALUE PARCEL (INTERSECTION)	$20,670,093,500	$3,189,941,400	$5,357,247,300	$6,485,310,600
TOTAL VALUE PARCEL (CENTROID)	$20,670,093,500	$627,145,700	$2,225,096,200	$3,860,392,700

Table 46 below summarizes the monetized values, derived from Tables 44 and 45 for the assets at potential risk of SLR and flooding for assets located in the HR region and Norfolk. The dollar loss values reflect the valuation of the potentially exposed developed land and property parcels for Mid-level SLR risks (based on the risk scenarios for exposure to 1 meter (3.3 feet) SLR above Spring High Tide.)[176] The table underscores the greater vulnerability of Norfolk compared to the HR region as a whole: Norfolk faces the potential loss of approximately 10 percent of its assets (value between $1.3B and $2.2B) compared to the regional exposure levels of about 7 percent of the properties.

Table 46. Potential asset loss for Norfolk and HR properties from exposure to SLR risks (Source: HRPDC (2012))

ASSET LOSS MEASURES (MID-LEVEL EXPOSURE RISK)	NORFOLK POTENTIAL $ LOSS VALUE (% TOTAL ASSETS)	HR REGION POTENTIAL $ LOSS VALUE (% TOTAL ASSETS)
IMPROVEMENT VALUE (CENTROID)	$1.3 B (9.6%)	$8.8 B (6.9%)
TOTAL VALUE OF PARCEL (CENTROID)	$2.2B (10.6%)	$16.5B (7.7%)

[176] Note that the differential influence of "intersection" and "centroid" is reflected in estimates of loss values for the three Low, Middle, and High scenarios (but the values are reported as equal for both rows).

Estimating Transportation Exposure and Business Losses due to Flooding in Norfolk

A recent study examined flood risks to electrical power, telecommunications, transportation fuels, and transportation under a 100-year flood scenario (i.e., an event that has a 1 percent chance of occurring in any given year possibly caused by a hurricane or nor'easter) under three sea level rise scenarios, including an increase of +0 feet (i.e., today's conditions), +1.5 feet, and +3 feet.[177] The analysis illustrated which assets within these sectors were potentially exposed to flooding (see Figure 36). In addition, the study used the Regional Economic Accounting (REAcct) Tool to estimate the regional and national economic impacts associated with the flood event under various SLR scenarios over a four-day period. REAcct is an Input-Output (I-O) model that provides regional or county-level estimates of direct and indirect impacts of the firms whose businesses have been adversely impacted by the disruption. The tool has a two-prong approach: (1) calculates the number of employees directly impacted by the event through GIS analysis, and (2) estimates the indirect impacts on the region's firms.[178] Indirect impacts are calculated by applying Regional Industrial Multiplier System (RIMS) II Input-Output multipliers which "are ratios of the total change to the initial change in regional economic activity."[179]

[177] Sandia National Laboratories (2016).
[178] Sandia National Laboratories (2011).
[179] Bureau of Economic Analysis (2013).

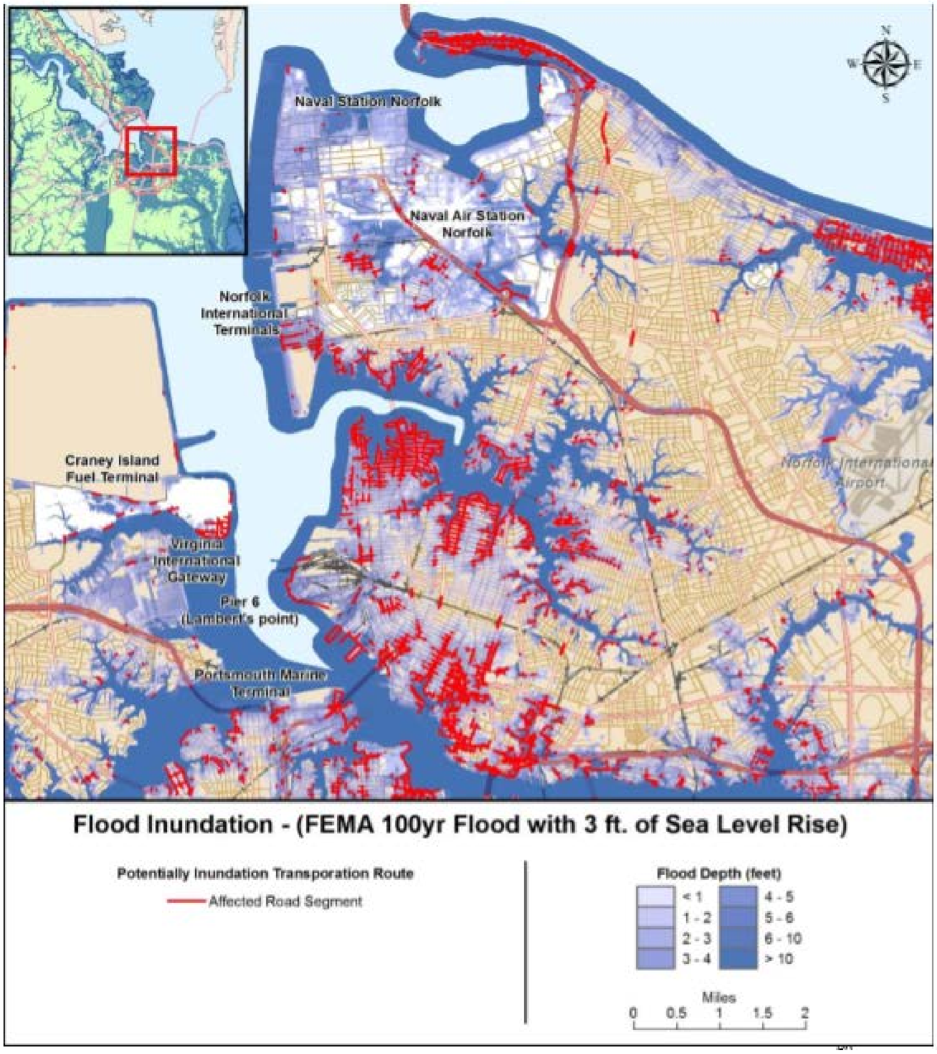


Figure 36. Transportation paths impacted by flooding with overlay of +3ft scenario (Source: Sandia National Laboratories (2013))

This analysis found the transportation sector being strongly at risk to potential flooding. From the exposure portion of this analysis, five of the nine major bridges and tunnels in HR were identified at a high flood risk to the 100-year flood (see Table 47).

Table 47. Major bridges and tunnels in Hampton Roads with anticipated risk of closure due to the 100-year flood (Source: Sandia National Laboratories (2011))

Bridge Name	Route	City/County From	City/County To	Expected Flood Risk
Hampton Roads Bridge Tunnel	I-64	Norfolk, VA	Hampton, VA	High
Monitor Merrimac Bridge Tunnel	I-664	Suffolk, VA	Newport News, VA	High
Berkeley Bridge and Downtown Tunnel	I-264	Norfolk, VA	Norfolk, VA	High
South Norfolk Jordan Bridge	Rte. 337	Chesapeake, VA	Portsmouth, VA	Med
Midtown Tunnel	Rte. 58	Norfolk, VA	Portsmouth, VA	High
High Rise Bridge	I-64	Chesapeake, VA	Chesapeake, VA	Med
Gilmerton Bridge	Rts. 460, 13	Chesapeake, VA	Chesapeake, VA	Low
Chesapeake Bay Bridge Tunnel	Rte. 13	Virginia Beach, VA	Kiptopeke, VA	High
Norfolk Southern Railroad Bridge	NS Rail	Norfolk, VA	Norfolk, VA	Med

Specifically:

- Roadways/Highways:
    - Two bridge-tunnels that provide access to the Virginia Peninsula (between northern and southern HR) are at high risk for closure under all future scenarios. A possible alternative route could be over the James River Bridge on Route 17/Route 32 which has a lower risk level.
    - Not only were coastal roadways at risk to flooding but so were inland roadways, particularly ones in Western Norfolk and along Elizabeth River. These flooding situations can create choke points and hot spots for travelers.
    - Bridges over Elizabeth or Lafayette rivers may be closed largely cutting-off travelers to/from downtown Norfolk and around Old Dominion University.

- Rail line:
    - Much of the Norfolk Southern rail line is not at risk for flooding except the crossing of the Elizabeth River.
    - Possible flooding where the rail line at points where it crosses Wayne Creek, Gilligan Creek, and Elizabeth River.

- Ports and Piers:
    - Intensive flooding of western Norfolk Peninsula affecting the use of Lambert Point's Coal Terminal.
    - Roadways within the Norfolk International Terminal (NIT) facility to the south and west of the rail line are at risk for flooding.

Hampton Roads. Industry losses for HR were estimated as a consequence of the disruption to electrical power, telecommunications, transportation fuels, and transportation. Figure 37 shows estimates of direct losses of the top 5 industries in HR as a consequence of a 4-day business disruption for three exposure scenarios for SLR (0 feet, 1.5 feet, 3 feet) combined with the 100 year flood. In the Professional/Technical sector, for instance, the region's direct losses would range between $34M and $58M depending on the storm intensity scenario.

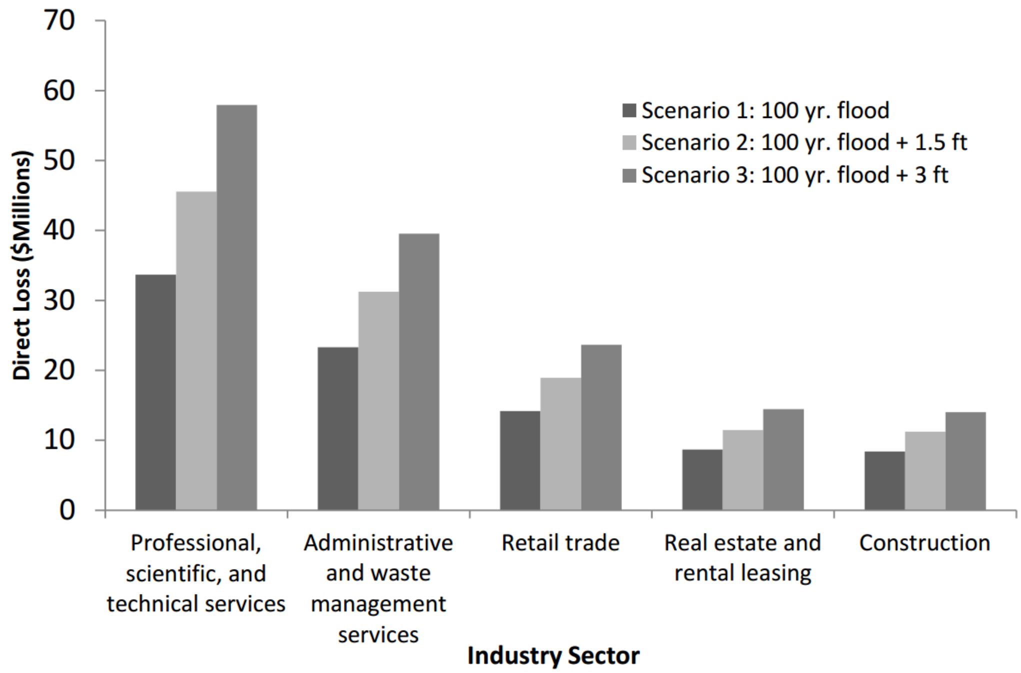


Figure 37. Top 5 direct losses in HR, as a consequence of a four day business interruption under three exposure scenarios (Source: Sandia National Laboratories (2011))

Norfolk. Total potential business losses in Norfolk, i.e. direct and indirect, were also estimated for the 4-day disruption. Potential direct losses ranged between $27M and $56M, depending on scenario (see Figure 38). The direct cost, however, accounted for only 38% of the total losses. When indirect costs - incurred by an array of economic costs due to business interruption, loss of the means of livelihood and access to job and mobility - were added to direct property losses, the total losses from direct and indirect damages rose by a factor of 2.6, with a range between $70M and $144.6 M, as summarized in Table 48. Indirect costs were estimated using the Regional Industrial Multiplier System (RIMS II).

Table 48. Estimates of direct and indirect losses in Norfolk for a four day business interruption under three scenarios (Source: Sandia National Laboratories (2011))

	Scenario 1	Scenario 2	Scenario 3
Annual Direct Losses	$26.92M	$39.71M	$55.60M
Annual Indirect Losses	$43.08M	$63.49M	$89.00M
Total	**$70.0M**	**$103.2M**	**$144.60M**

Comparing Norfolk with four other HR jurisdictions, Virginia Beach has the greatest direct loss associated with business disruption followed by Norfolk (see Figure 38). This suggests these two jurisdictions may be at greatest risk during flood events, which may then be further exacerbated by SLR.

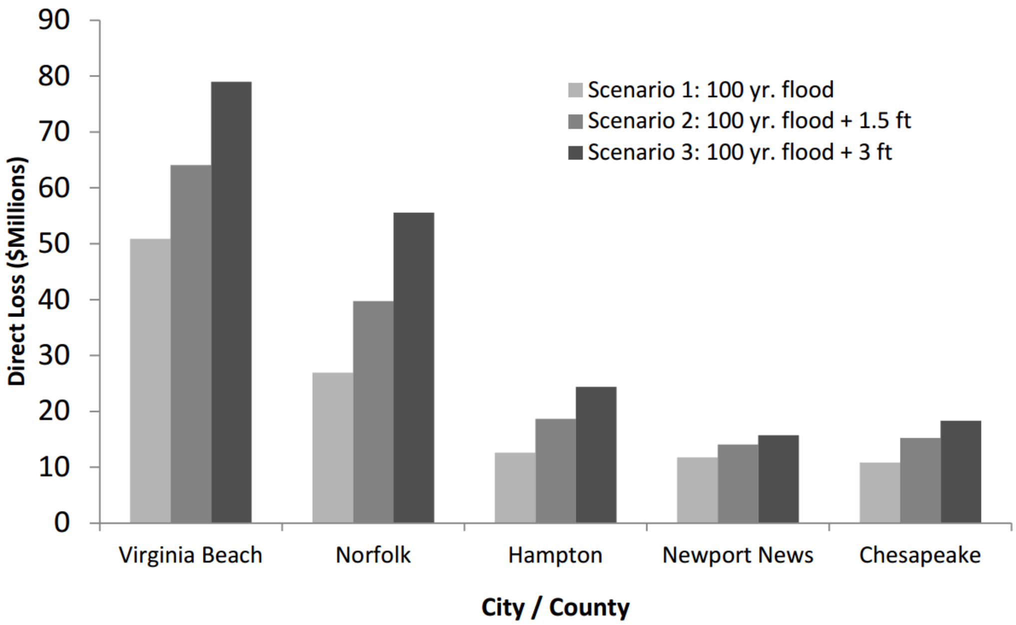


Figure 38. Top five HR cities ranked by direct losses due to four days of disruption (Source: Sandia National Laboratories (2011))

Military Sector

The implications of the changes in DOD spending and employment on current and potential future economic conditions in HR, and in Norfolk in particular, have been examined in Sandia's study of the economic impacts of SLR. The Sandia study underscored the extent to which the Norfolk's economy is intertwined with the Naval Station, noting that the Naval Station's functions play a key role in the regional economy, generating a significant multiplier effect in additional jobs and revenues. Implementing adaptation projects in Norfolk to mitigate the SLR and flooding risks, the report concluded, will have beneficial impacts beyond protecting the Norfolk International Terminal (NIT) container shipping operations (see textbox).

> *Norfolk operates as a major cog in the Hampton Road's port machine. Because of this, protecting Norfolk from flooding will protect approximately half of Hampton Road's coal shipping capacity, half of its container shipping capacity… Norfolk is innately intertwined with successful operation of NAVSTA Norfolk and supporting facilities… Norfolk's flooding resilience will have an impact to the individuals that work and serve at these facilities, as well as the facilities themselves.*
>
> Source: Sandia National Laboratory (2016).

As for the role of the region's transportation network on the military facilities' exposure to risk, the HRPDC 2034 Long Range Transportation Plan (LRTP) has identified six key locations in the Norfolk network of highway tunnels and bridges that represent significant traffic delays and capacity constraints for military operations.[180] These six Norfolk-area military facility capacity problem areas were: [181]

- The I-564 Inter modal connector;
- The Air Terminal Interchange;
- South Norfolk Jordan Bridge;
- Midtown Tunnel;
- Improved Harbor Crossing (with Third Crossing);
- I-64 Corridor Expansion.

1-5 DATA ON ADAPTATION IN HR

There are multiple planning avenues for considering adaptive strategies, including key strategies that reduce the impacts, and those that mitigate the consequences (see Figure 39). Such strategies can be introduced at many entry points of an assets lifetime such as during the planning, procurement process, design, construction, maintenance, repair, and operations. A number of metrics can be considered when weighing which adaptive strategies may be best such as economic costs, environmental consequences, social justice issues, etc. This section considers past efforts in HR for quantifying the economic costs and benefits associated with adaptive strategies for various purposes. This information provides invaluable dollar estimates of potential strategies relevant to the region.

[180] The report also stressed the need to extend the Light Rail extension to Naval Station Norfolk, and the need for high-speed intercity passenger rail service connecting HR to Richmond, DC, and beyond, since having the ability to conduct travel to key regional points by rail (and conduct a full day's business in DC without an overnight stay) yield substantial cost saving benefits.
[181] HRTPO (2012a).

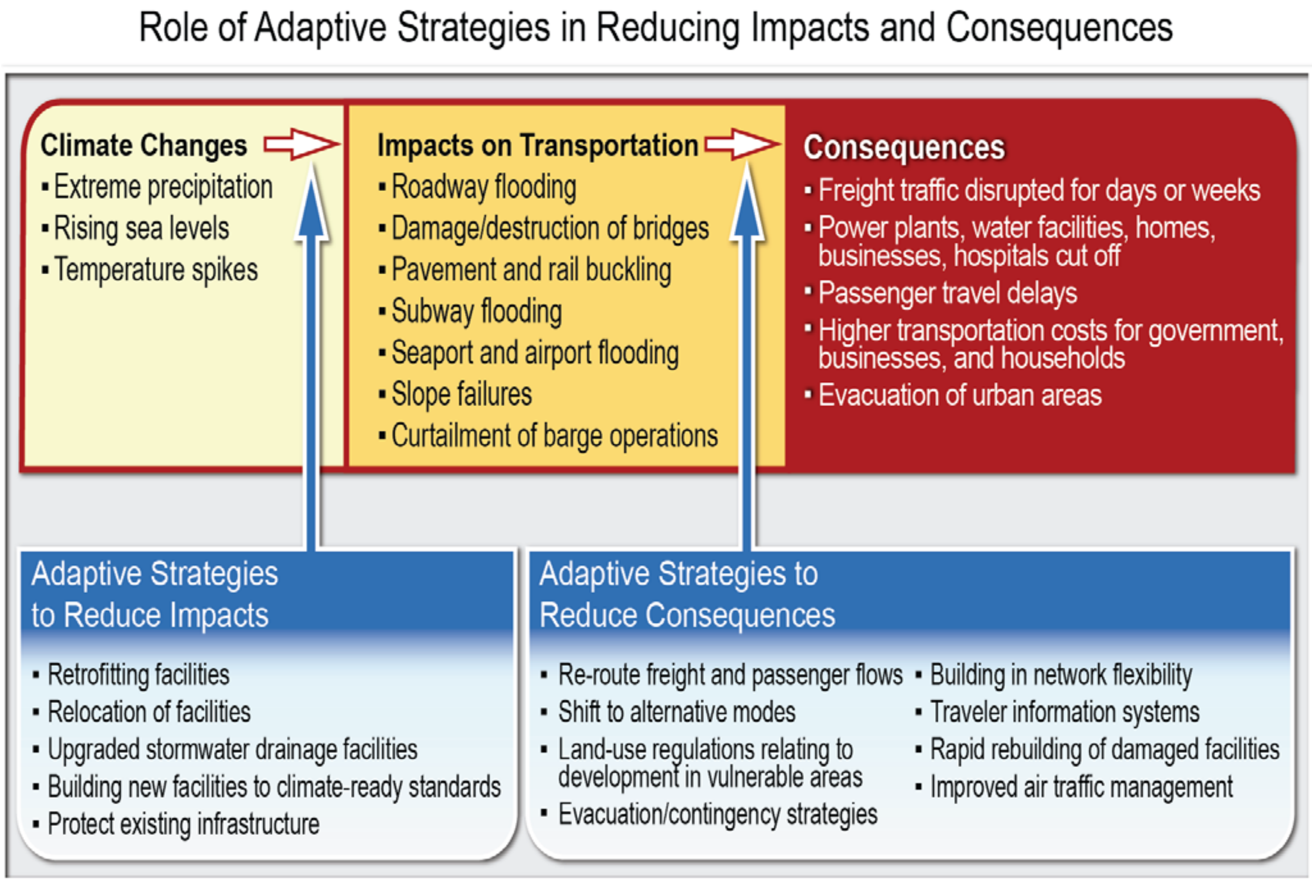


Figure 39. USGCRP view of climate change adaptation components (Source: U.S. Global Change Research Program (USGCRP) (2009))

"Buying Down" Flood Risk

One example of the risk-reduction strategy is the USACE's promotion of the concept of "buying down" a region's flooding risks. The strategy consists of a systematic process for reducing flood risks that includes: calculating the difference in the magnitude of the estimated costs of *Initial Risk* and the remaining *Residual Risk,* by quantifying the cumulative impact of the adaptation measures implemented. The table below describes the 6 of the 8 components of the process for assessing risks and vulnerabilities, calculating the consequences of each measure, and then, more effectively dealing with the diminished residual risks of the region flooding, depicted as the 6th component of the risk-buying down process. It should be noted that the contribution of insurance to mitigating flooding risks represents only a transfer of damage costs, and to this extent would overestimate the total cost-saving benefits.

Example of mitigation and adaptation actions for USACE defined risk and reduction tools

Risk Components	Mitigation and Adaptation Actions
1 – *Initial Risk*	Inventory of existing conditions and vulnerabilities: fragile levees, erosion of system design standards, aging infrastructure, underfunded maintenance projects, environmental threats, urbanization
2 – *Zoning*	Flood plans and zoning, 200-year flood plans for minimum protection for urban areas, amendments to zoning ordinances, shared liability of state and localities, designation of floodways
2 – *Building Codes*	New building standards, incorporation of climate change/SLR into codes and standards
5 – *Insurance*	Flood plain mapping, annual flood risk notification
6 – Non-Structural	Home relocation, raising or buyouts (reduce flood damage)
7 – Structural	Beachfill or breach contingency plans (reduce flood impact)
8 – *Residual Risk*	Financials costs and consequences of damages

Source: USACE (n.d.).

1-5-1 Existing Adaptation Measures for City of Norfolk

Norfolk prepared a report on Coastal Resilience Strategy,[182] a report that documented the existing adaptation measures, including the plans for a half-mile long floodwall in downtown Norfolk with five tide-gates and a pump station for draining runoffs. The City planning projects include these structural projects:

- Raising road on Brambleton Avenue to allow improved access by raising the roadway to nearby medical complex ($2.4M);
- Building flood walls, earthen berms, gates, pumps and elevating electricity structures (potentially underway, with costs estimated between of $10M to $306M);
- The USACE conducted a study of the OceanView beaches to inform Norfolk's flooding plan, resulting in a proposal of Norfolk's first "*engineered beach*" (with the estimated construction cost of $18.4M with a city share of $5.5M; accounting for 30 percent of total costs);
- The USACE study of The Hague and Pretty Lake projects for SLR and flooding protection, where the agency will pay for a large portion of the costs.[183]

Identifying the need for adaptive strategies

Coastal Resilience Index, developed by Mississippi-Alabama Sea Grant Consortium and NOAA's Coastal Storms Program, helps a community self-evaluate how prepared it is for coastal hazards from extreme events. The index is calculated based on stakeholder responses to an 8-page self-assessment tool of predominantly yes/no questions. The goal of this effort is to enhance effective communication within communities and identify any gaps in preparedness. This tool may prove useful in identifying potential adaptive strategies.

1-5-2 Flood Mitigation for City of Norfolk

The engineering firm Fugro has also completed a flood mitigation study for Norfolk. The study involved installing and monitoring new long-term tide gauges, developing a GIS platform for a flood model, conducting coastal engineering evaluations to define flood exposure and prioritize projects, and developing an interactive predictive flood impact model. The study included five structural adaptation projects for building:

- A floodwall to protect against tidal surge;
- Tide gates for navigation access;
- A pump station to remove rainfall runoffs;
- Berms and closure walls to protect against low watershed perimeter;
- Raised roads as protection against flooding.

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[182] Norfolk, City of (n.d.).

[183] Other estimates of adaptation costs: Wetlands Watch reports that the Norfolk Naval Station has been spending an estimated $35M to $40M to replace piers vulnerable to inundation. The Naval Air Station Oceana in Virginia Beach and Dam-Neck Annex are also reported to be threatened by SLR "encroachment", as it was previously by the encroaching residential developments threatening its move.

The Fugro plan focused on four areas within Norfolk: Mason Creek, Pretty Lake, The Hague, and Ohio Creek. The engineering area of focus represents only 18 percent of the size of the city, but includes 16,126 structures, 14,993 of which are residential. Two of the three neighborhoods in the study, The Hague and Pretty Lake, contain about 9,000 structures. The study recommended a capital project to protect Pretty Lake against coastal flooding and runoff, including: construction of a tidal barrier to protect against surge; a tide gate to preserve navigation; a pump station to remove rainfall when the gate is closed; and raised roads where the land surface is too low around the watershed perimeter. Norfolk's low-income neighborhood of the 1970s-era townhomes was hit by extensive flood damage several times. The City Council members have advocated buying out and razing the structures. The Fugro study recommended a three-phase approach for at-risk neighborhoods:

- Phase 1: the buyout of the most vulnerable properties;
- Phase 2: installing a pump station to reduce rainfall impact during tidal surge; and
- Phase 3: installing a box culvert to improve the drainage system.

The four project areas were as follows:

- Hague Flood Wall – preliminary design completed; estimated costs $60M.
- Pretty Lake Flood Wall – preliminary design; estimated cost: $50M;
- Mason Creek Pump Station – cost: $30M;[184]
- Ohio Creek (also known as Spartan Village) – for improvements in a tidal area that has been most at risk from repetitive flooding.

The total adaptation costs for three of the above projects in the Fugro study were estimated at $140M. The engineering firm also estimated the benefit-cost ratio for some of the projects is as high as 2:1.[185] By one estimate, the capital costs for the three projects account for 2.8% of the assessed value of the properties in the three Norfolk neighborhoods (not including the Ohio Creek project), as summarized in Table 49.[186]

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[184] This is a capital project intended to protect against rainfall runoff (area protected from tidal surge by an existing Tidal Gate (operated by the Navy) that will require: a pump station to remove rainfall runoff when gate is closed; a new storm culvert beneath the Navy berms and peripheral wall when land surface is low around creek; involves street elevating and future improvements).

[185] Although the city currently has a city-wide freeboard requirement of 1 foot, they are looking at increasing it. Norfolk was the earliest jurisdiction in HR to reference the issue of SLR. The city is taking on a number of projects that will increase its resilience, including creating a living shoreline along Haven Creek and making drainage improvements. In addition, the city is replacing and elevating a bulkhead 1.5 to 2 feet above the existing bulkhead at a cost of $440k, as well as installing a mobile pump to deal with tidal flooding.

[186] In Norfolk alone, a consultant has identified $1B in Protection improvements on the Lafayette Watershed in floodgates, berms and drainage improvements. (Source: VA Chamber Foundation (2015)).

Table 49. Proposed Norfolk flood control engineering projects (Sources: Norfolk, City of (2012a), Norfolk, City of (2012b))

CITY OF NORFOLK NEIGHBORHOOD	PROPOSED ADAPTATION AND MITIGATION PROJECTS	ASSESSED PROPERTY VALUE IN THE WATERSHED	ESTIMATED COST	PROJECT COST AS % OF PROPERTY VALUE
THE HAGUE	• Floodwall • Tide gate • Pump Station • Berms/Closure walls	$1,624 M	$60 M	3.7%
PRETTY LAKE	• Floodwall • Tide Gate • Pump Station • Structure elevation	$1,812 M	$50 M	2.8%
MASON CREEK	• Pump Station • New storm culvert • Peripheral Berms • Structure elevation	$1,604 M	$30 M	1.9%
TOTAL	NA	$5,040 M	$140M	2.8%

Evaluating Drainage Projects in The City of Norfolk

The *2012 City-Wide Drainage Study* identified a total of 253 drainage projects, and evaluated flooding risks caused by rain. The scoring and prioritization criteria were based on the following eight criteria in as shown in the Table below. The findings suggest that about 150 miles of roadway need some form of drainage and roadway improvements, costing $561.6M. These improvements do not include possible utility improvement projects, pumps stations or outfall improvements.

Prioritization criteria for Norfolk city-wide drainage study. (Source: Norfolk, City of (2012))

Prioritization Criteria	Maximum Score
Identified complaints/flooding events + maintenance needs	30
Location of completed/planned CIP project	20
Existing infrastructure capacity per acre of developed area	20
Portion of the drainage designated to pass a 10-year storm (those not passing were assigned a higher #)	15
Infrastructure condition (those with poor condition got a higher score)	15
Road classification (winter vehicular moves and ER/evacuation impacts)	15
Critical infrastructure (fire, police, hospitals, etc. get a higher ranking)	15
Presence of Business Development Focus Area	10

Source: Norfolk, City of (2012c).

1-5-3 Hampton Boulevard Corridor

Another study on the Norfolk SLR adaptation projects is the case study of the Hampton Boulevard Corridor.[187] Hampton Boulevard starts along Norfolk Naval Station and leads to the Midtown Tunnel. The Port Authority Police and Old Dominion University are also located along this residential route. The Boulevard is near the coastal Lafayette and Elizabeth Rivers, making it vulnerable to flooding, even absent rain events, when high tides range from 2 to 8 feet, disrupting traffic along the road for an extended period of time. The study team developed estimates of project cost and type, including:

- **Flood barriers between Craney Island and Port Authority**. Estimated cost of the 1.53-mile structure is $2B. The design of this project replicates the Maeslantkering Barrier in the Netherlands, a structure that is machine operated, equipped with sensors that would provide warning of the tidal rise at Sewells Point, automatically signaling the need for the barrier to close at the anticipated SLR, when the gates are closing, the barrier floats until it is securely closed, then sinks into place where it will block the surge of high tide. The gate will stay open to navigation during normal tide conditions. The project will require construction of man-made islands on either sides. The project costs are high relative to smaller alternative projects and would require extensive maintenance.

- **Bioretension Basin Rain Garden System**. This is a system that works by directing the storm water to the basin, where it percolates through the rain garden and is treated through biochemical and natural process. The treated water then infiltrates and is directed to nearby storm-water drainage, directing the water away from vulnerable infrastructure. By slowing down the runoff, the basin relocates the storm water, purifies it to reduce the nitrogen and phosphorous levels of the storm water and sediments. Currently, one project in Norfolk, the Blue Bird Park Stormwater Wetland Construction project, at an estimated cost of $84,500, is currently in the development stage. Also, Myrtle Park Wetland restoration project is underway. Together these projects will be effective in redirecting some of the storm water. The City is currently pursuing a policy of encouraging residents along the Boulevard to construct rain gardens on their property to help prevent straining the drainage system capacity and extend the projects' life span.

- **The Lafayette River Flood Wall.** This project is designed to protect homes along the end of the river without destroying the area's natural beauty. The proposed Wall ranges from 3 to 10 feet in height and cost $110 to $400 per feet in length. The Wall's engineering requirements are stringent, given the need to prevent seepage of water through assembled segments.

- **A Flap-type Flood Barrier operated by a Hydraulic Cylinder.** This barrier lies flat on the seabed beneath the Hampton Boulevard Bridge, and will rise up to block the excess inflow of water when a storm surge or high-tide is predicted. The barriers will control the fluctuation of water levels when it is elevated. The barrier's design is similar to the Thames River Barrier in U.K. and the Stamford

[187] University of Virginia (2015).

Hurricane Barrier in Connecticut. (The project costs are expected to be less than the more elaborate Craney Island Barrier.)

Protecting Against SLR: Adaptation Costs

NOAA's evaluation template for protecting against SLR contains five types of adaptation:

1. *Managed Retreat*: transfer of development rights; purchase of rights; relocation;
2. *Tidal Management*: storm surge barriers;
3. *Engineered Barriers*: levees and dikes; sea-walls; beach nourishment; sand bagging;
4. *Infrastructure Modification and Design*: elevated development; flood-proofing facilities; floodable developments; floating developments; movable structures;
5. *Land-Use Policy and Zoning.*

Example of generic cost ranges for Tidal Management and Engineered Adaptation Options:

- *Storm-Surge Barriers*: can be a fixed structure (e.g., a closure dam) that is permanently closed, or movable gates or barriers that can be opened and shut. These are high cost: from $0.7M to $3.5M per meter, plus annual maintenance; effective in reducing the surge; downside: potential environmental and waterway damage;
- *Beach Nourishment*: costs: $300-$1,000 per foot;
- *Seawalls*: $150-$4,000 per linear foot;
- *Levees and Dikes*: $100-$1500 per foot;
- *Engineered Developments*:
  - Elevated structures: $2,000-$30,000;
  - Floating developments: $2,000-$30,000;
  - Floatable developments: can be cost effectively implemented during design/construction;
  - Drainage systems: costs vary;
  - Flood proofing: can be cost effective and implemented as part of the design/construction.

Source: NOAA (2013).

Example: Adaptation in NYC

ClimAID produced the following adaptation solutions for New York City:

- Seal ventilation street grates for subway systems in flood zones, and replace passive open ventilation with forced closed vents;
- Install flood gates at vulnerable entrances;
- Build berms and levees;
- Update flood maps to show flood elevation for 100- and 500-year recurrences and add projections on SLR;
- Implement design and retrofit transportation infrastructures for adaptive resilience;
- Update emergency response plans;
- Alternative plans, including barriers to protect the entire New York harbor and estuary, similar to London's Thames barriers.

Post-Sandy damage evaluations demonstrated the high effectiveness levels for two adaptation measures:

- Temporary barriers at the Harlem River Tunnel prevented flooding of subway lines between Manhattan and the Bronx;
- Removing sensitive signal and control systems from most tunnels expected to be flooded, and reinstalling them after the storm—proved highly effective in keeping signals free of damage from salt water, saving one or two weeks of recovery time and an estimated $10B in damages.

Source: New York State Energy Research and Development Authority (2011).

1-6 CHALLENGES WITH QUANTIFYING COST BURDENS

1-6-1 Challenges with Economic Loss Associated with Recurrent Flooding

A major consequence of recurrent flooding is that many damages remain unpaid, which in turn makes it harder to quantify the cost burden of extreme weather events and determine the full extent of the needed adaptation measures. In 2009, Norfolk reported 280 "frequently flooded" or "repetitive-loss properties" that needed some form of flood mitigation. The National Flood Insurance Program (NFIP) has defined "repetitive losses" as "properties that have experienced at least two paid flood losses of >$1000 each in any 10-year period since 1978." In the 2013-2014 period, the repetitive loss estimate in Norfolk had risen to 900 structures, more than a threefold increase. In addition to Norfolk, four other HR cities were reported to have experienced a total of 2,979 repetitive property losses which were not compensated by private insurance or NFIP. Together these repetitive property-damage events incurred a total of $431M in uncompensated costs, creating a large gap between what FEMA paid and what was needed for flood mitigation improvements. FEMA, under its Hazard Mitigation Assessment (HMA) program, provides post-hazard grants to states/localities through a competitive process.[188] The FEMA HMA funds have not kept pace with the increased rate of flood damage. The FEMA HMA funds only apply to the insured structures, and do not cover costs of roads and transportation infrastructure mitigation projects, which need to be funded by other funds (if at all), typically out of the local government's Capital Improvement Plan (CIP), transportation improvement plan (TIP), or storm water funding. Virginia's Revolving Fund (for water, dam safety, and clean water), and more recently, Green Bonds,[189] have historically been used to pay for these damages. Table 50 shows the scale of repetitive-loss properties, and the gap between the needed mitigation funds and the compensations paid by FEMA, in Norfolk and four other HR cities.[190]

Table 50. 2013-2014 property loss data on repetitive loss properties (Source: Wetlands Watch (n.d.))

HR CITY	# OF REPETITIVE LOSS PROPERTIES	AVERAGE COST OF MITIGATION (000)	TOTAL COST OF MITIGATION (000)	AVERAGE FEMA FUNDING
CHESAPEAKE	409	$250	$102,250	$757K
HAMPTON	863	$75*	$64,725	$833K
NORFOLK	900	$162.5	$146,250	$778K
PORTSMOUTH	186	$75	$13,950	$NA
VIRGINIA BEACH	561	$185	$103,785	$725K
TOTAL HR	**2,979**	**NA**	**$430,900**	**NA**

**Average statewide mitigation cost of $75,000 was used for localities where data were not available.*
Figures do not include unclaimed damages.

1-6-2 Private Insurance

Compounding the role of uncompensated repetitive flood damages, and high levels of economic disadvantage, is the availability of insurance. Because of the public-goods character of much of infrastructure systems in HR exposed to SLR and flooding risks, it is often difficult to assign property rights and responsibility for paying for the damage costs. Though the insurance industry provides a substantial contribution to rebuilding after an extreme storm, in some instances, the government and the public may incur a greater amount of the cost burden. For example, a recent National Resources Defense Council (NRDC) paper has maintained that in the aftermath of the 2012 Hurricane Sandy the common claim by the insurance industry was that the major share of the damages—at a total cost of $139 billion, considered the 2nd costliest climate disaster in the U.S.—was paid for by private insurance.[191] However, the researchers found that the private insurance payout amounted to only $33 billion (24%), with the largest share, $96B (69%), paid out of the public coffers, as Table 51 shows.

[188] The FEMA HMA grant program covers installation costs of flood vents, elevating utilities, elevating structures, and outright purchase of property.
[189] Green Bonds are bond whose proceeds fund environmentally friendly projects. They were first issued by World Bank, but now many banks and governments issue them. Vienna was the first local government in Virginia to issue Green Bonds, in 2015.
[190] Wetlands Watch, (n.d.); The uncompensated-loss estimate was based on applying an average loss estimate of $143,700 per property. The report points out that FEMA's NFIP premiums have been scheduled to rise (effective 2013) in all Virginia coastal areas. The report estimates that it would take FEMA between 78 and 188 years to clear the backlog of flood damage improvement needs.
[191] NRDC (2013).

Table 51. Allocation of the 2012 Hurricane Sandy cost burden (Source: NRDC (2013))

SOURCE OF PAYMENT	COST BURDEN ($BILLIONS)	% SHARE
PRIVATE INSURERS	$33	24%
US TAX PAYERS	$96	69%
UNINSURED	$10	7%
TOTAL STORM-RELATED COSTS	**$139**	**100%**

This type of analysis is important when considering who will incur the cost burden in the aftermath of an extreme weather event (e.g., is it the same parties that pay for an adaptive strategy that reduces harm and associated costs).

How do Private Insurers Measure Risk?

Risk is the difference between expected outcomes and potential outcomes. The expected loss is calculated by multiplying the probability of an outcome by the cost of that outcome, and summing all the multiples. Then the standard deviation is calculated to measure the potential variability. The greater the variability, the greater the risk.

For example, an insurance company might consider the potential costs of flood damage associated with varying levels of flood (e.g., nuisance flood, 20-year flood, 50-year flood, 100-year flood). The potential costs of flood damage for varying levels of flood can be calculated by first determining the likelihood of whether the home will flood (e.g., is the home is located in a flood-prone area as illustrated by FEMA's Flood Insurance Rate Maps (FIRM)). Then, determining the consequence if a flood were to happen using FEMA's depth-damage curves for the type of house (e.g., a graph that shows the depth of the flood water from 0 to 10 feet and the associated costs of damage that may be incurred for a one story home without a basement). The insurer may then determine the average flood damage that may occur over a window of time. The more individuals living along the coastline from the Gulf Coast through the Atlantic that can be insured, the greater the reduction of the insurers risk. For example, if a storm were to occur, it is assumed only a portion of the insured collection of homes would be damaged.

For additional insight on how private insurance view risk of flooding events, see Appendix E.

Source: Anderson et al. (2005); Per communication with Mr. Steve Kolk, Assistant Vice President of Pricing American Integrity Insurance Group.

PART 2 – OVERVIEW OF ECONOMIC METHODOLOGIES AND ASSESSMENT RESOURCES

There are a number of pathways to consider when quantifying the direct and indirect economic costs associated with transportation climate resilience. This discussion considers the direct and indirect costs of an extreme event and the direct and indirect costs and benefits of adaptive measures.

The direct and indirect costs of the event, in the "business as usual" case, includes the consequences of a severe weather event such as repairing damage to transportation infrastructure, associated fatalities and injuries, which have relatively straightforward methods for their calculation. Consequences can also include related effects such as traffic delays or less-tangible effects such as environmental or quality of life degradation.

The direct and indirect costs and benefits of, in essence, protecting a community against the impacts of a catastrophic event on transportation infrastructure ("adaptive strategies" or "alternatives") may be considered at various entry points, which are prior to the anticipated threat occurring (including short-term and long-term planning), during the exposure to the threat, or soon after the threat has occurred. For example, tangible costs incurred due to storm surge of an event could include fatalities and injuries and traffic delays while intangible costs might be the loss of environmental services or degradation of quality of life. There are a number of economic analyses to choose from when considering transportation investments involving adaptive strategies for coping with the impacts of climate change. It's important to note that in some instances, the proposed adaptive measures may be cost-effective even without considering climate change.[192] These measures may be considered "no-regrets," as the benefits associated with implementing such strategies are realized under current and future conditions regardless of future outcomes. In these instances, there is a strong economic case for immediate action.

2-1 PRIMER ON ECONOMIC METHODOLOGIES

This section reviews the conventional economic analyses used by transportation agencies for quantifying transportation investments and suggests ways these analyses may be used in a climate risk framework.[193]

Traditionally, economic analysis has been used to inform transportation decision making. For example, economic analysis might be used to demonstrate whether a potential transportation project makes economic sense to pursue considering the monetized costs and benefits over the serviceable life cycle of an asset. In considering costs, there are a number of metrics that can be quantified for transportation costs analysis at the

[192] Swiss Reinsurance Company (2011).
[193] Note that this discussion is not intended to discuss regulatory requirements for providing costs and benefits required for federal project funding.

agency-level, facility operations-level, and by transportation users (see Table 52). These metrics fall under the general categories of: construction, rehabilitation, and maintenance activities.

Table 52. Costs and benefits that can be quantified for transportation cost analysis (Source: adapted from USDOT (2003))

Agency Costs	• Design & engineering • Land acquisition • Construction • Reconstruction/rehabilitation • Preservation/Routine maintenance • Mitigation (e.g., noise barriers)
Users **Costs / benefits**	• Travel time (Facility operations) • Delay (Facility operations / Work zones) • Crashes (Facility operations / Work zones) • Vehicle operating costs (VOC) (Facility operations / Work zones)

In an economic analysis, agency costs represent the costs of the transportation project, while facility operation and user costs represent the benefits (this assumes that the project would reduce the impacts/costs to the facility operation and user). Transportation analysts measure the project costs and benefits by calculating the value of "C" as the sum of agency costs and social costs (e.g., traffic delays) and the value of "B" as the social benefits (as the sum of all avoided user costs).

Terminology and Metrics Useful for Economic Analysis

Inflation: measures the rise of prices for most goods and services. Best practices suggest: (1) not to account for inflation when forecasting life-cycle costs/benefits in an economic analysis (i.e., work with today's base year dollars); (2) include inflation in the project budget if the findings of (1) suggests economically viable project. There are simple formulas that can be used to adjust prices for inflation.

Is Inflation Removed from value?	Appropriate Dollar Terms to Use
Yes	• Real • Constant • Base year
No	• Nominal • Current • Data year

Discount Rate: is a rate that represents the time value of money. For example, money can be loaned or invested. If money is invested, there is an expectation of growth suggesting an amount of money today will be worth more in the future (perhaps growth of 5% per year). In the absence of inflation, if this money was loaned instead the money would not grow unless there was some agreed upon annual rate of return (e.g., 5%). When working with future dollars, a discount rate may be applied to estimate the present value. Because the choice of discount rate can have significant impact on estimating present value of costs and benefits, the discount rate should be a good representation of a State's actual time value of resources.

Simple Project Metrics

Net Present Value of Benefits (NPV): This metric takes the difference of the present value (PV), i.e., using a discount rate, of all costs and benefits of a project's lifecycle. If the benefits exceed the costs the NPV is positive and the project is worth pursuing.

$$NPV = Benefits - Costs$$

Benefit-Cost Ratio (BCR): This metric takes the ratio of the present value of the benefits to the present value of the initial agency investment cost. The ratio is usually expressed as a quotient (e.g., B $2M/C $1M = 2.0). This metric is used to select among projects when funding restrictions apply. For a given budget, the projects with the highest BCR can be selected, or used to form a package of projects that yields the greatest multiple of benefits and costs. If you are selecting more than one, normal practice is to group all the projects into bundles that are within the budget constraint, and see which collection gives you the greatest net benefit. Using B/C ratios doesn't get you there.

$$BCR = \frac{Benefits}{Costs}$$

Source: USDOT (2003).

The following economic analysis are useful for comparing transportation investments:

- Life-Cycle Cost Analysis (LCCA)
- Benefit-Cost Analysis (BCA)
- Economic Impact Analysis (EIA)

Each of the analysis is discussed in detail below. These analyses can generally be scaled to support varying levels of complexities, tailored to the specific project being analyzed.

2-1-1 Life-Cycle Cost Analysis (LCCA)

This method is an analysis, used in a wide range of governmental and industrial applications, that can be used to estimate the costs associated with the various choices (or "alternatives") to accomplish a given project or objective.[194] For example, an LCCA may be used when an agency has decided to move forward with a project and wants to compare the alternatives to identify the most cost-effective alternative. The LCCA sums the initial costs and future costs over the project's viable life; under conditions that the benefits are assumed to be equal among all projects. Essentially as a cost-only subset of Benefit-Cost Analysis discussed in the next section, LCCA identifies the most affordable means of accomplishing the proposed goal. For example, an LCCA may consider the life-cycle costs of building a tunnel.

Quantifying Direct Economic Impacts: LCCA

LCCA can help select across alternatives when benefits are essentially equal.

Uses in Climate Vulnerability/Risk Analysis

- Comparing adaptive strategies for a given asset

This analysis does not traditionally consider indirect costs.

Typical costs are summarized in Table 53, though only costs which will vary across the alternatives need to be included in the LCCA. The greatest variation of costs across alternatives tends to be user travel delay costs[195] and agency costs of construction and rehabilitation.[196] User crash costs tend to be omitted because of the substantial uncertainty in estimating these numbers; however, in a simple analysis, there may not be much variation across alternatives.

[194] USDOT (2003).

[195] The user costs vary across alternatives generally due to varying work zone requirements across alternatives. User vehicle operation costs in work zones may be small compared to travel delay costs. This cost can be estimated within a good degree of accuracy. USDOT (2003).

[196] USDOT (2003).

Table 53. Transportation costs that may be used in a LCCA (Source: adapted from FHWA (2003))

Agency Costs	• Design & engineering • Land acquisition • Construction • Reconstruction/rehabilitation • Preservation/Routine maintenance
Users **Costs / benefits**	• Delay (Work zones) • Crashes (Work zones) • Vehicle operating costs (VOC) (Work zones)

The LCC for a transportation project can be represented symbolically: [197]

$$LCC = \sum_{k=-(m-1)}^{n} C_k \frac{(1+j)^k}{(1+i)^k}$$

where *m* is the number of years in the development/acquisition phase, *n* is the operational lifetime, *i* is the discount rate, *j* is the inflation rate, and C_k is the cost incurred in the k^{th} year.

Life-Cycle Costs Analysis Steps

1. Establish design alternatives
2. Determine activity timing
3. Estimate costs (agency and user)
4. Computer life-cycle costs
5. Analyze the results

Source: US DOT (2002).

Applying this formula requires the following steps: (i) estimate of the useful life of the project; (ii) estimate of the yearly costs over the life-cycle; (iii) choice of a discount rate; and (iv) choice of an inflation rate.[198] The second step of estimating yearly costs over the life-cycle of the project can be the most challenging part of the LCCA. By including inflation in step iv, the yearly costs are estimated for nominal dollars. Office of Budget and Management's Circular A-94 provides standard and sensitivity cases for discount rates and future inflation that may be used in practice. [199]

Though LCCA can provide a useful estimate for comparing the costs of project alternatives, there are challenges,[200] the operational lifetime can be difficult to accurately forecast, particularly for projects considering new materials. The operational lifetime can also be problematic to estimate if future use could change substantially. For example, accurately projecting operational lifetime may be challenging for a project building a new coastal roadway that services a population whose neighborhood is projected to be underwater due to SLR between 2040 and 2060. To address this, it is general practice to adopt a standard value for operational lifetime. In addition, there can be substantial uncertainties in choosing an appropriate discount and inflation rate.

[197] Eisenberger and Lorden (1977).
[198] Eisenberger and Lorden (1977).
[199] Office of Management and Budget (2015).
[200] Eisenberger and Lorden (1977).

2-1-2 Benefit-Cost Analysis (BCA)

Benefit-Cost Analysis (BCA) estimates both the life-cycle benefits and life-cycle costs of an individual project or objective. This is used to compare alternatives for a project when the benefits are not identical or across projects that may have different objectives. The goal of using a BCA is to identify the alternative that maximizes the net benefits to the public from the allocation of resources.[201]

Transportation-related attributes that can be monetized include: "travel time costs, vehicle operating costs, safety costs, ongoing maintenance costs, and remaining capital value (capital expenditure and salvage value)."[202]

Quantifying the Direct Economic Impacts: BCA

BCA can help select across alternatives when benefits are not equal.

Uses in Climate Vulnerability/Risk Analysis

- Comparing adaptive strategies across assets and locations

This analysis does not traditionally consider indirect costs.

The benefits and costs typically considered in the alternatives are summarized in Table 55. When conducting a BCA, one of the alternatives developed is termed the *base case* and represents the "do minimal option", i.e., "the continued operations of the current facility under good management practices but without major investment." The other alternatives may be representative of adaptive measures. The major steps in a BCA are provided in the adjacent textbox.

There are a few considerations when conducting a BCA. (1) Many projects that use BCA or LCCA for investment evaluation do not consider the deterioration of the facility conditions over time, thus underestimating the user-costs. (2) As with the LCCA, the alternatives in a BCA may have varying operational lifetimes. To account for this, a multiyear analysis period is adopted for consistent comparison across alternatives. (3) When user benefits are large, it may be important to also consider forecasts of changes in traffic patterns to ensure an accurate assessment. The textbox entitled, "DOT Economic Analysis In Action", below describes the economic analysis of five recent DOT climate resilience pilots. The formulas and methodologies developed in these analyses are helpful building blocks to inform a "full" regional economic quantification analysis.

Major Steps in the Benefit-Cost Analysis Process

1. Establish objectives
2. Identify constraints and specify assumptions
3. Define base case and identify alternatives
4. Set analysis period
5. Define level of effort for screening alternatives
6. Analyze traffic effects
7. Estimate benefits and costs relative to base case
8. Evaluate risk
9. Compare net benefits and rank alternatives
10. Make recommendations

Source: USDOT (2003).

[201] USDOT (2003).

[202] Minnesota Department of Transportation (2016).

DOT Economic Analysis in Action

Over the past decade, the Department of Transportation (DOT) has conducted a number of climate resilience pilots across the United States. A few of these pilots considered economic impacts associated with potential adaptation projects (also termed “alternatives”):

- **The Minnesota DOT pilot**: This pilot used the COAST benefit-cost tool to evaluate the economic impacts of potential adaptation projects. COAST calculates the cumulative damages to transportation facilities over time using curves of water depths as a function of storm probabilities (e.g., 10-year storm) and curves of water depths as a function of damage costs (i.e., depth-damage functions). This study estimated the facility costs incurred from an event (e.g., flooding) over the lifetime of the facility as the “base case.” The damage costs include physical damage costs, travel time delay costs, potential for motorist injury and fatalities. A discount rate of 2% was applied to translate future dollar estimates to present value costs. Then, for each adaptation option considered, the benefits (i.e., costs avoided) versus the incremental costs under possible future climate scenarios are calculated. The costs of each adaptation option was compared to the base case to identify cost savings. The benefit-cost ratio was then compared across the adaptation options to determine cost-effectiveness. The preferred adaptation options were ones with a benefit-cost ratio above 1 and were robust against the range of future climate scenarios.
- **The Oregon DOT pilot**: This pilot used a benefit-cost analysis (BCA) to compare a baseline approach to a “permanent fix” adaptive strategy. The benefits included time savings, reduction in vehicle operating costs, and increases in safety. The costs were either maintenance costs for the baseline approach, or the costs of the adaptive strategies.
- **The New York State DOT pilot**: This pilot used a BCA and considered both direct and indirect costs and benefits. Three categories of benefits were included social, economic, and environmental. Social benefits included safety, mobility, and accessibility to critical services, such as hospitals; economic benefits included avoided flood repair costs, avoided costs to repair environmental degradation, and avoided freight disruption; and environmental benefits included healthier fish and wildlife, improved river habitat, less erosion, improved water quality, and increased river recreation. Social and economic benefits were calculated in dollar values. Environmental benefits were included by using a multiplier.
- **The DOT Gulf Coast Phase 2 study**: This study used a Monte Carlo analysis for conducting the BCA. The Monte Carlo process is used when the exact input values are unknown. The analysis considers the possible variation across a range of inputs to create many outcomes. Then those outcomes are processed and analyzed to create a probability distribution of outcomes.
- **The DOT Hillsborough pilot**: This pilot used the Regional & Economic Models, Inc. (REMI) tool to calculate the economic losses associated with the disruption of specific vulnerable transportation facilities and the cost-effectiveness of adaptation strategies. REMI was driven with inputs of hours of travel time delay, vehicle miles traveled, and lost commuter and truck trips to provide changes in Gross Regional Product (GRP), income, and labor hours over a five-day (business week) period.

Source: MnDOT (2014); Oregon Department of Transportation (2014); NYSDOT (2016); USDOT (2014); Hillsborough County MPO (2014).

For additional information regarding FHWA pilots, see:
http://www.fhwa.dot.gov/environment/climate_change/adaptation/resilience_pilots/index.cfm

Recognized Limitations with NPV, LCCA, BCA

There are limitations of the conventional BCA, Net Present Value (NPV) and LCCA methods for determining transportation network costs and benefits, including the open-ended range of agency-costs and user costs that can potentially inflate either the full project costs or its benefits, depending on how they are manipulated. To avoid these pitfalls, the USDOT FHWA has recommended that two improvements be made to the process of cost analysis:

1) Only the initial agency investment cost be included in the denominator of the ratio; with all other BCA values (including periodic rehabilitation costs or user costs such as delays associated with construction) to be included in the numerator as potential positive or negative benefits; and
2) To avoid overestimating the benefits of a project, care should be taken not to include as "benefits" what is simply a restatement of what has been calculated as part of an economic impact study as benefits of job and business growth (and added to safety and travel time savings) to avoid potential long-term double-counting of the benefits.[1]

Source: USDOT (2003).

[1] The Texas Transportation Institute (TTI) has developed the MicroBENCOST model to implement the AASHTO guidelines for measuring user benefits from highway projects.

2-1-3 Economic Impact Analysis (EIA)

Given some of the limitations of conventional BCA and LLCA methods of calculating project costs and impacts, an economic impact analysis (EIA) may be preferred as this analysis incorporates broader indirect measures of economic and climate-change impacts on the transportation infrastructure performance and costs. For example, an EIA may include monetary effects on employment patterns, wage levels, business activity, tourism, and housing.[203] In other words, an agency might first conduct a BCA to monetize the direct economic impacts of a project, and then use these results to inform the EIA which monetizes the related indirect economic impacts (e.g., jobs, land-use, etc.). An EIA is a "complimentary analysis to the BCA."[204] EIA integrates travel demand models, land-use, and dynamic input-output economic interaction. It is important to note that the monetary value of the indirect effects in an EIA is not additive to the value of BCA-measured direct effects. Faster commuting time,

Quantifying the Indirect Economic Impacts: EIA

EIA can enhance a BCA by considering the costs associated with the indirect economic impacts across alternatives.

Uses in Climate Vulnerability/Risk Analysis

- Comparing adaptive strategies across assets and locations

This analysis traditionally can include direct and indirect costs/benefits.

[203] USDOT (2003).
[204] USDOT (2003).

for instance, may induce more people to move further away from work place; this new demand for more remote properties drives up the price of remote property. Thus the highway user translates part of the value of his travel time savings to the owners of suburban properties. An EIA is conducted when a project is justified not solely on the benefits generated at the project level, but when broader benefits can accrue, or damages are averted.[205] An EIA is also useful for providing additional information when there are competing interests supporting various alternatives of a project.

There are a number of EIA methodologies, including:[206]

- Survey studies: This is a qualitative approach drawing on expert interviews, vehicle origin-destination logs, corridor information, etc.
- Market studies: This "consider[s] demand and supply for business activity to quantify market of a change in transportation costs caused by a project."
- Comparable case studies: This "evaluate[s] the localized economic impacts of a project on neighborhoods, downtowns, or small towns [(e.g., bypassing a small town)]."
- Sophisticated econometric analysis and economic modeling, including productivity impact analysis (considering productivity benefits not generally included in a BCA) and regional economic models.

As the need for greater precision and analytical breadth of BCA tools grows, more sophisticated EIA studies are done with Input-Output models that capture aggregate regional economic effects.

Input-Output (I-O) models are a type of regional economic modeling and are readily available economic analysis tools that enable consideration of broad range of direct and indirect economic impacts resulting from an infrastructure disruption. I-O models are static, in that they provide a "snapshot" of economic effects in reaction to a disruption (i.e., they do not provide the potential cumulative economic effects over time). This suggests these models are particularly useful for considering the short-run impact of a given extreme event or under a future scenario where adaptation strategies were implemented and the extreme event occurred under future conditions (e.g., sea level rise). Input-Output models such as Regional Input-Output Modeling Systems, 2nd edition (RIMS II) and Impact M for Planning (IMPLAN) are among commonly deployed tools for estimating the full impacts of changes in the transportation network on the regional economy. The advantage of I-O models is that they can be applied to any geographic level where Bureau of Economic Analysis (BEA) data are available. Refinements of I-O models can focus on specific segments of the transportation network, ports, rail facilities, power stations, etc., at the regional or sub-metropolitan level.[207]

Data sources for I-O models include BEA data on flows of production inputs (raw materials, labor, etc.) and output (services and manufactured products) in the region. BEA provides measures of the annual national

[205] USDOT (2003).
[206] USDOT (2003).
[207] BEA data sources include National Income Accounts, Satellite Accounts, I-O Accounts, and Tradestats Express database containing data on imports and exports at the national level and exports at the state level.

output by NAICS (North American Industry Classification System) industry class. Using these data, I-O models such as RIMS II, IMPLAN, and Regional Economic Model, Inc. (REMI) provide output- and demand-driven multipliers to indicate the extent to which each dollar of direct spending circulates in the economy to generate additional income benefits in the region. These I-O models and CGEs are described below.

Economic impact metrics commonly quantified by the tools described in this section

- **Direct economic impact***,* measured by multiplying the region's GDP per worker/per day by industry sector (transport sector in general or specific subsectors ports, etc.) output times the number of lost worker days. Summing this across all affected sectors yields the total direct GDP costs;
- **Indirect economic impact***,* measured as indirect loss in other related sectors and households through losses of input materials purchased, lost incomes (which affects spending across all industries);
- **Induced impacts** are the losses from reduced activities of other sectors resulting from the damages to the facilities of the primary sectors directly impacts;
- **Total impacts** are estimated by multiplying the direct impacts by the RIMS II multipliers. These multipliers translate a dollar of direct economic impact in a region/industry into a total economic impact. These multipliers simulate the successive rounds of expenditures taken place through the economy as a result of a change in expenditures in an industry/region. The estimated indirect impacts are then determined by subtracting the direct impacts from the total impacts.

Regional Input-Output Modeling System (RIMS II)

RIMS II, developed and maintained by the Department of Commerce, is a fee-based data service by the U.S. Bureau of Economic Analysis (BEA). BEA is the primary agency of the federal government that compiles economic information. BEA also produces the Benchmark Input-Output (I-O) accounts of the U.S. Economy, which are used for building I-O models. [208] RIMS II provides a regionally- or state-specific set of total final demand multipliers for total industrial output; value added; earnings (labor income); and jobs (so that users can use them rather than generating their own multipliers).[209] The model is based on an I-O table that shows the industrial distribution of inputs purchased and inputs sold for any of up to 369 detailed industry sectors. The inputs include not only the costs of raw materials for production, but also labor (household sector). Data from RIMS II show the multipliers for each dollar spent on inputs and outputs to represent the extent to which every dollar of change in an industry's input and output affects all other industries. As such, the multipliers quantify the way a dollar injected into one sector is spent and re-spent in other sectors, generating subsequent activity that affects the entire regional economy. RIMS II's advantage is that it uses readily

[208] See: http://www.bea.doc.gov/rims.

[209] (Note: Availability of RIMS II through the BEA has been discontinued because of sequestration and reduction in FY 2013 funding levels. Unless funding is restored at some future date, RIMS II will not be available.)

available BEA data sources, is a simple to use spreadsheet-based tool, and is relatively inexpensive, costing between $2K and $5K.

Impact Analysis for Planning (IMPLAN)

The Minnesota IMPLAN Group's Impact Analysis for Planning (IMPLAN) is a computer-based economic impact analysis model that uses data sources readily available from BEA, with the capability for modification of the regional or national variables. IMPLAN calculates the impacts of a change in its inputs and outputs, displaying them as traditional direct, indirect, and induced effects.[210] Through its Social Accounting Matrix (SAM) modeling, the I-O table accounts for all dollar flows between different sectors of the economy; using this information, IMPLAN models the impact of the economic multiplier throughout the region. A key capability of IMPLAN is the spatial definition of the area of analysis, which in IMPLAN can range from state to county to zip code. Unlike other static I-O models that just measure the purchasing relationships between industry and household sectors, SAM also measures the economic relationships between government, industry, and household sectors, allowing IMPLAN to model transfer payments such as unemployment insurance. IMPLAN is a more expensive I-O tool ($5K-$15K) than RIMS II but has the advantage of allowing a dynamic application of the multipliers to the impacted industries.

Regional Economic Models, Inc. (REMI)

Regional Economic Models, Inc., or REMI is a comprehensive economic accounting model that relies on the BEA data on employment wages, and personal incomes to estimate the impacts of a change in demand or supply of inputs through five sets of metrics: 1) output; 2) labor and capital demand; 3) population and labor supply; 4) wages/prices/profits; and 5) market shares. Relative to other economic modeling tools, REMI is expensive, costing between $2k and $100k.[211]

Computable General Equilibrium (CGE) Models

CGE models have been introduced in recent years to supplement I-O models for impact analysis, providing the capability to predict the behavior of businesses and individuals when faced with a disaster. CGE is a "multi-market simulation model based on simultaneous equations optimizing behavior of individual consumers and firms, subject to economic accounts balances, and resource constraints." CGE models provide a valuable framework for analyzing natural hazard impacts and policy responses, and measuring the effectiveness of adaptation responses. These models incorporate micro-, meso-, and macro-level effects through the business production response to aggregate categories of major inputs of capital, labor, energy, materials, and transportation subgroups.[212]

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[210] Induced impacts in some models have been interpreted as the "catalytic effects" models that estimate the "net economic effects (employment, income, government revenues) resulting from the contribution of expansions in a transportation system such as air transportation on tourism and trade, and its long-term effects on GDP and productivity. These effects may be construed as "spillover" effects that are not measured through their direct or indirect impacts.

[211] Citizens Climate Lobby (2014).

[212] Rose and Lia (2005).

At the regional level, data can be obtained on two key components of loss from a disaster: a) flow measures: e.g., output, income, and employment losses, which are just as important as b) stock measures of loss to property and infrastructure assets. The stock and flow measures can take into account the full range of economic assets and actual and potential losses (including loss of use and loss of consumer surplus) for the region. CGE models can also incorporate capital-asset losses (discounted flows) of present and future value of flow disruptions, as well as un-priced non-market values and externalized losses. Such capabilities make CGE models able to potentially mimic the role of markets and prices. To this extent, CGE models are dynamic and might be able to account for an entirely new path of economic growth. In other words, the IO models tend to me more rigid but valuable for a short run analysis, while the CGE models may provide more information about responses over time, as market adapt to new conditions.

2-2 RESOURCES FOR ASSESSING TRANSPORTATION ASSET VULNERABILITY AND QUANTIFYING ECONOMIC IMPACTS OF CLIMATE CHANGE

> *Approaches to climate change are shifting from a disaster-response-focused approach to a risk-management approach that seeks to build resistance to climate-induced impacts through making systems more robust and resilient.*
>
> Source: Field et al. (2012).

Several useful tools have been developed in the past decade that can be adapted to consider and/or quantify the impacts of extreme weather and/or climate change on the transportation system and the associated economic consequences. Prior to an economic analysis, there needs to be an understanding of which transportation assets or systems are vulnerable to a changing climate or extreme weather event and potential adaptive measures that may enhance resilience. To date, transportation climate assessment studies follow a variety of methods dependent on purpose and expertise. However, underlying these choices tend to be the fundamental steps as illustrated in the Department of Transportation (DOT) Adaptation Framework (see Figure 1). Some of the resources available for assessing vulnerabilities and considering adaptive strategies include the following tools developed by USDOT and NCHRP:

- Vulnerability Assessment Scoring Tool (VAST): Provides a framework to evaluate potential climate-related vulnerabilities across transportation assets. In addition, VAST provides a library of generic sensitivity and adaptive capacity indicators across transportation asset type and climate stressor. VAST could be enhanced by using economic drivers as additional criteria in identifying critical assets and associated sensitivities and adaptive capacity.

- Costing Asset Protection for Transportation Agencies (CAPTA): Provides a framework that could be tweaked to identify adaptive strategies that may make economic sense in addressing the impacts of climate change.

Once the vulnerable assets of greatest concern are identified along with a collection of potentially economically viable adaptive strategies, an economic quantification at either the asset or programmatic level can be conducted. Figure 40 provides a qualitative illustrative example of one way these tools could connect.

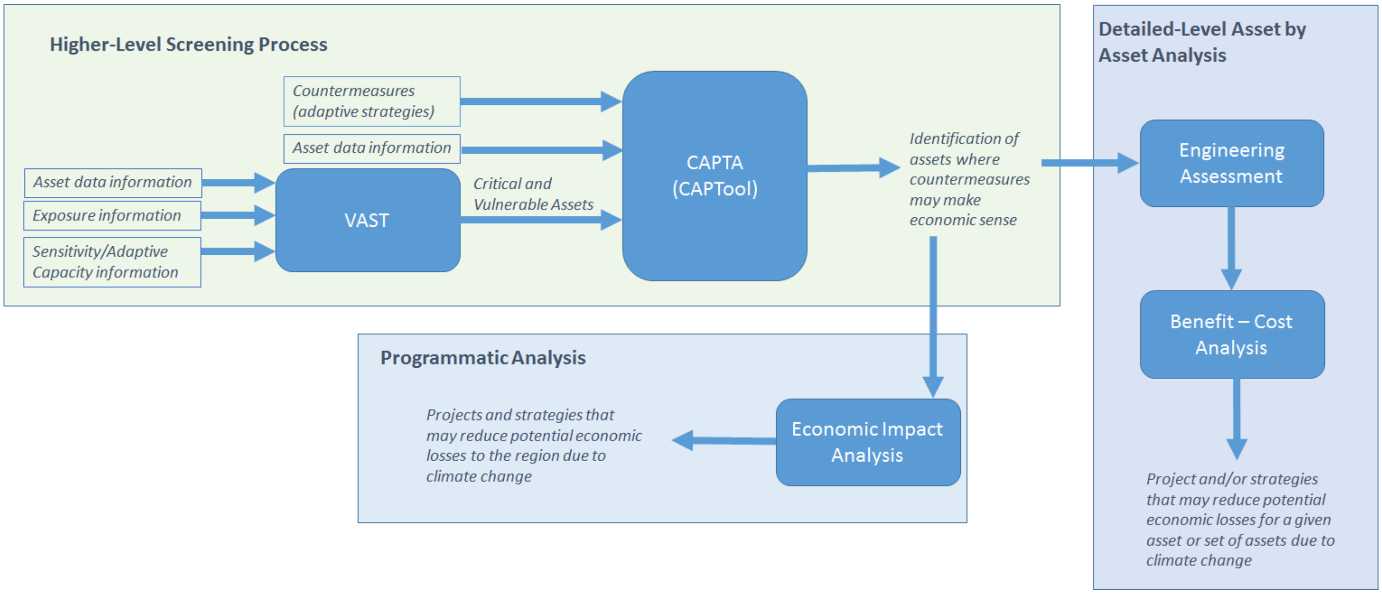


Figure 40. Schematic of pathway the tools discussed in this section may inform economic analysis at program or asset level (Source: based on discussion provided in this section)

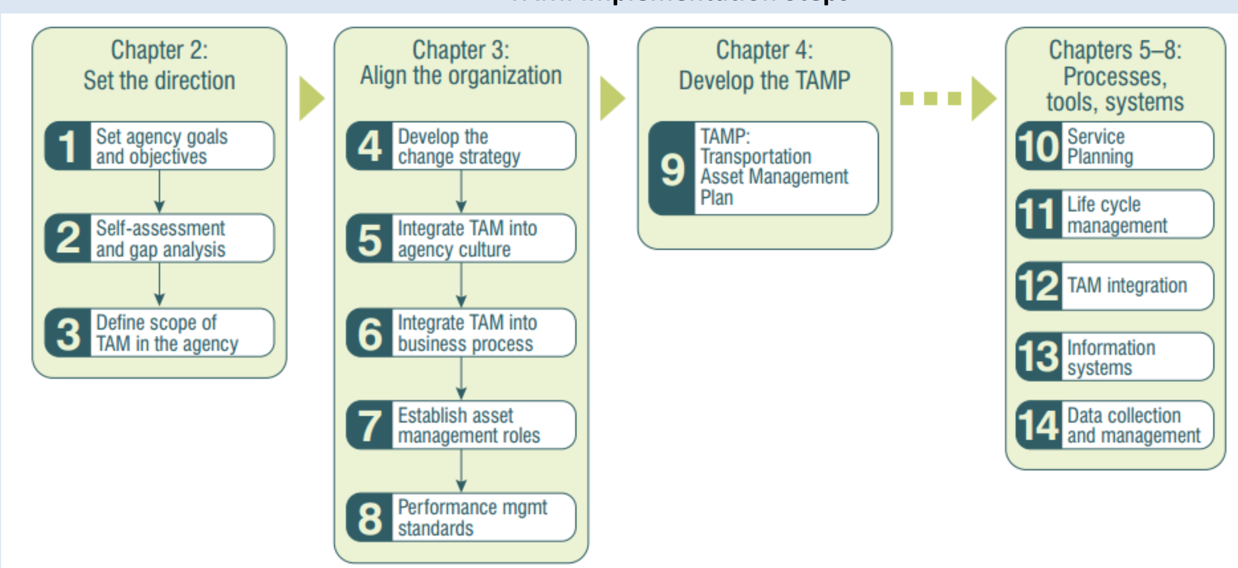
Resources for Asset Management and Planning

Preparing for Natural Disasters. In compliance with the Presidential Policy Directive 8 (PPD-8) requirements for nation preparedness, FEMA worked with interagency partners to develop the National Disaster Recovery Framework (NDRF). The framework is a report that guides disaster-affected states, tribes, or local-communities through effective pre- and post-recovery, including the transportation infrastructure.

Transportation Asset Management. For decades, state DOTs have been conducting transportation asset management (TAM) as part of the decision process for investment in maintenance and capacity enhancement projects. With implementation of the Moving Ahead for Progress for the 21st Century Act (MAP 21), TAM moved closer to incorporating climate-related risks into its asset management decision process.

In 2012 and 2013, FHWA used TAM as a platform for evaluating and addressing extreme weather impacts by releasing a series of reports on risk-based asset management. TAM's applications for managing risks can be broken down into 14 main steps, with each step setting the direction for aligning the agency's project investments with the organization's asset-management responsibilities (see Figure below). TAM's final five steps articulate the extreme weather risk-management steps—service planning, life-cycle management, and the steps leading to integration of climate-related information systems and data-collection functions into TAM. These functions have been consolidated into the TAM Information System or (TAMIS), a tool that integrates the agency tasks relating to climate change risk into the state TAM functions. The TAMIS tool incorporates four datasets—asset inventory, inspection, condition, and work history—each of which is a key source of information on extreme weather events, asset vulnerabilities, and potential adaptation measures.

TAMI Implementation Steps



Source: American Association of State Highway and Transportation Officials (AASHTO) (2011).

2-2-1 The VAST Tool

The Vulnerability Assessment Scoring Tool (VAST) was developed by USDOT for use by planners and asset-managers to assess how assets in their transportation system may be vulnerable to climate stressors. This spreadsheet-based tool does not consider event-related or adaptive costs and benefits; it is a tool for identifying which assets may be most vulnerable when populated with user information. VAST uses indicators to develop quantitative vulnerability scores for five categories of assets: roads, ports, airports, rail, and transit. The USDOT Gulf Coast Phase 2 Study developed VAST as an asset-specific vulnerability model that identifies characteristics that serve as indicators of their exposure, sensitivity, and adaptive capacity.[213] A Vulnerability Score for each critical asset is based on the vulnerability formula:[214]

Vulnerability = f (Exposure, Sensitivity, Adaptive Capacity)

VAST identifies exposure levels, asset sensitivity, and capacity to adapt; and produces a scoring dashboard to reflect the scale of threats and mitigation measures (see Figure 41).[215] The example dashboard shows a summary of the vulnerability of roads to temperature change, precipitation change, and storm surge. Each climate stressor is considered with two scenarios representing a small amount of future change (e.g., "low scenario") and a larger amount of future change (e.g., "high scenario"). This is a technique that many within the climate planning community use to bound the future plausible futures based on the state of the science. To arrive at these results, the user has already tailored VAST with exposure indicators (e.g., temperature change may use "maximum high temperatures sustained over three days" as an indicator), sensitivity indicators (e.g., 3-day temperatures above a given threshold(s)), and adaptive capacity.   In this example, storm surge only affects a portion of the study area, in which case some roads entered in VAST are simply not exposed to storm surge. The vulnerability scoring is from 0 to 4, with 4 representing the most vulnerable.

Asset Types

- Rail lines
- Ports
- Airports
- Transit assets
- Buildings
- Boardwalks
- Bridges
- Culverts
- Docks
- Parking lots
- Pavement
- Pavement inlets
- Piers
- Pipes
- Retaining wall
- Signs
- Storm sewer pipes
- Trains
- Traffic signals
- Tunnels
- Other (User-defined)

Climate Stressors

- Temperature Change
- Precipitation Change
- Sea Level Rise
- Storm Surge
- Other (User-defined)

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213 USDOT Gulf Coast Phase 2 Study website: https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/.

214 FHWA; Mike Savonis, ICF International.

215 USDOT (2015).

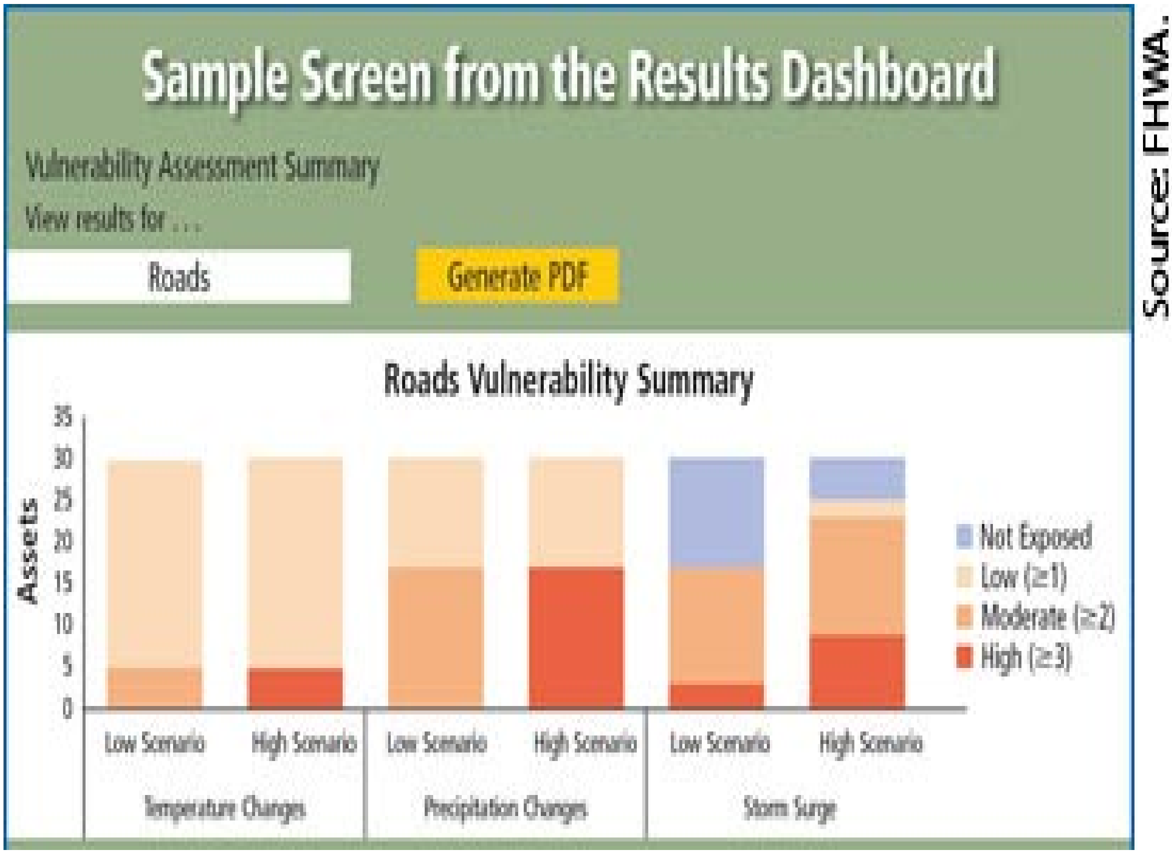

Figure 41. VAST dashboard. (Source: USDOT)

VAST requires the user to populate the tool with quite a bit of information; however, this allows for a flexible and tailored analysis. First, the tool requires that asset managers collect a range of asset data (see Table 54).[216] The exposure information can be collected or processed through various sources as described in the user's manual, including DOT's Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool which processes a number of climate models to obtain a set of future changes for temperature and precipitation variables. [217]

[216] USDOT (2015).

[217] The World Climate Research Programme's (WCRP) fifth phase of the Coupled Model Inter-comparison Project (CMIP5) provides a standardized experimental protocol for studying the output of climate models developed by 20 modeling groups. For the United States, many of these large-scale climate model output of daily temperature and precipitation have been downscaled to fine-scale climate model output using a statistical technique based on gridded observations. DOT FHWA provides a tool, the CMIP Climate Data Processing Tool, for post-processing this fine-scale climate data to provide transportation-relevant climate stressors (e.g., number of days per year above 95^{o}F). This tool is part of CMIP Data Processing Tools available at FHWA's climate adaptation website.

Table 54. Types of data to be collected for VAST (Source: VAST User's Guide)

ASSET DATA	ADDITIONAL DATA
▪ AGE OF ASSET ▪ GEOGRAPHIC LOCATION ▪ ELEVATION ▪ CURRENT/HISTORICAL PERFORMANCE AND CONDITION ▪ LEVEL OF USE (TRAFFIC COUNTS, FORECASTED DEMAND) ▪ REPLACEMENT COST ▪ REPAIR/MAINTENANCE SCHEDULE AND COSTS ▪ STRUCTURAL DESIGN ▪ MATERIALS USED ▪ DESIGN LIFETIME AND STAGE OF LIFE	▪ LIDAR (LIGHT DETECTION AND RANGING) REMOTE SENSING DATA ▪ FEDERAL EMERGENCY MANAGEMENT (FEMA) MAPS ▪ VEGETATION SURVEY

VAST suggests a number of exposure indicators for precipitation and temperature (see Table 55). The temperature exposure indicators can be processed using climate model outputs, such as through the DOT CMIP Climate Data Processing Tool. There are a number of sources that can be used to inform the precipitation exposure indicators, such as: DOT CMIP Climate Data Processing Tool, FEMA Digital Flood Insurance Maps (DFIRMs), flood insurance studies, feedback from maintenance and emergency management staff, and local universities. The scoring of these indicators is from 1 to 4 with 1 suggesting no significant change in exposure and 4 suggesting significant exposure.

Table 55. List of exposure indicators provided in the exposure indicator library in VAST (Source: VAST tool)

TEMPERATURE EXPOSURE INDICATORS	PRECIPITATION EXPOSURE INDICATORS
▪ Change in total number of days per year above/below a threshold temperature ▪ Change in longest number of consecutive days per year above/below a threshold temperature ▪ Change in number of freeze-thaw cycles per year ▪ Change in annual maximum and minimum temperature ▪ Change in annual mean temperature	▪ Change in amount of rain associated with 100-year 24-hour storm ▪ Location in FEMA 100-year flood zone ▪ Location in FEMA 500-year flood zone ▪ Location in 10-year Floodplain ▪ Location in 25-year Floodplain ▪ Change in Number of Consecutive Days with Precipitation ▪ Change in Total Seasonal Precipitation ▪ Change in Total Annual Precipitation ▪ Change in Peak Discharge ▪ Change in Flow Velocity ▪ Change in Discharge Volume

VAST suggests a number of sensitivity indicators by asset class and climate stressor (see Appendix D for a full table of sensitivities as provided by the VAST Tool library). For example, a sensitivity indicator for bridges might be truck traffic. For each sensitivity indicator included, the user must determine what ranges of values represent the 1 ("low sensitivity") to 4 ("high sensitivity") scores. VAST suggests a number of sources to assist in data development, such as: interviews/survey/conversations with operations and maintenance staff, maintenance or repair records, emergency response records, National Bridge Inventory, engineers, and owners and operators.

VAST further provides a library of adaptive capacity indicators that can be useful to collect. For example, an indicator of port adaptive capacity to an extreme weather event might be the redundancy within a facility. A cross-walk between these indicators and asset management information can be useful to identify most vulnerable assets.

2-2-2 CAPTA: A Consequence-Based Risk Management Tool

The National Cooperative Highway Research Program (NCHRP) report, "Costing Asset Protection: An All Hazards Guide for Transportation Agencies," (CAPTA) is a guide for transportation practitioners to evaluate the consequences of threats/hazards on critical multimodal transportation infrastructure assets. Part of this work included the development of the Costing Asset Protection Tool (CAPTool). The CAPTool is an asset management tool in the form of an Excel spreadsheet that provides a set of guidelines for identification of critical or high-cost assets and evaluation of the potential countermeasures (i.e., mechanisms for reducing harm).[218] The CAPTA methodology uses a standard risk model $R = f(T, V, C)$ for quantifying threats ("T"), vulnerabilities ("V"), and consequences ("C") to measure the community's relative susceptibility to the consequences of hazards. However, CAPTA is not intended as a formal risk model as it does not require the user to estimate the likelihood of the event but, instead, the user identifies the hazards of concern.[219]

CAPTA is a multi-step process starting with asset identification with the CAPTool automating a significant portion of the CAPTA methodology (see Table 56). [220] The CAPTool considers 8 asset classes - including road bridges, road tunnel, transit/rail bridges, transit/rail tunnels, transit/rail stations, administration and support facilities, ferry, and fleets. The user can select which asset classes are appropriate for the analysis and will then need to identify the critical assets that they want to consider in the analysis. The hazards/threats considered include:

- Natural events (flood, earthquake, extreme weather, mud/landslide);
- Unintentional events (fire, power loss, equipment breakdown, structural failure, hazardous material);
- Intentional threats (small explosive devices, large explosive devices, chemical/ biological / radiological agents, criminal acts).

Of these hazards/threats, the flood and extreme weather within the natural event category are directly applicable to the HR analysis of costs associated with climate-related events and adaptive measures. The CAPTool does not simulate what assets may be exposed during a flood event, but considers if a flood event

[218] NCHRP (2009).
[219] Though natural events have historical data that can be used to assess likelihood of the event, it is not included to maintain consistency across all threat categories.
[220] FHWA (2013a).

were to occur, which assets exceed the consequence thresholds (as described below) to warrant further consideration of countermeasure investments.

Table 56. CAPTA methodology with steps in yellow performed within CAPTool (Source: FHWA (2013a))

A.	Identify Assets
B.	Collect Data
1.	Identify Threat/Hazard Asset Classes (Relevant Risk Tab)
2.	Establish Consequence Thresholds (Thresholds Tab)
3.	Describe Infrastructure Assets (Multiple Assets Tabs)
4.	Identify Critical Assets Across Modes (Critical Assets Tab)
5.	Identify Countermeasure Opportunities (CM Opportunities Tab)
6.	Generate Summary Report (Results Summary Tab)
7.	Re-run CAPTool with Updated Assumptions, Budget Realities, or New Assets

A key component of CAPTool is the user-defined "Consequence Thresholds" for each asset-class considered. The Consequence Threshold is the point at which the impact of the threat/hazard is significant enough to warrant consideration of countermeasure investments. These thresholds include: potentially exposed population,[221] property loss,[222] and mission importance[223] (e.g., demand percentile for ADT*Detour Length for a road bridge asset class). In determining applicable hazard/threat thresholds, the user may also consider such information as the National Fire Protection Association, FEMA's National Flood Protection Act (NFPA) guidelines, or other engineering standards.

Table 57 outlines the components of the CAPTA consequence thresholds composed of three key decision factors: potentially exposed population (PEP), potential value of assets at risk of loss, and the mission-critical equation for bridge assets. CAPTool applies a series of equations to determine whether an asset is above the user-specified threshold consequence levels.

[221]Potentially exposed population refers to the population that could be harmed by the maximum threat/hazard. This consequence tends to be well-correlated with delays to emergency response, etc.
[222] Property loss is the cost to replace an asset type (units of millions of dollars).
[223] Mission importance describes the relative importance of the assets and the volume of use, including loss of function and/or transport delays. An exception is road bridges which considers the product of ADT and detour distance.

Table 57. Threshold consequence determination (Source: NCHRP (2009))

ASSET	POTENTIALLY EXPOSED POPULATION EQUATION	PROPERTY EQUATION	MISSION EQUATION
ROAD BRIDGES	Separated into primary direction and secondary direction – for each, if vehicles/lane >2400 assume 40 vehicles/1000 feet. Otherwise, if lower assume 7.5 vehicle/1000 feet.	$20,000/lane feet	(ADT) x (detour length) 75th, 85th, 95th percentile as thresholds relative to typical bridge inventory (Example is based on the National Bridge Inventory)
ROAD TUNNELS	See above	$100,000/lane feet	User input for criticality
TRANSIT/RAIL STATION	4 x (maximum capacity of rail cars)	Below ground = critical	User input if transfer station is critical
TRANSIT/RAIL BRIDGE	2 x (maximum capacity or rail cars)	$15,600/lane feet	User input is percentage of ridership that regularly use this transit/rail transportation asset
TRANSIT/RAIL TUNNEL	2 x (maximum capacity of rail cars)	$40,000/feet	User input is percentage of ridership that regularly use this transit/rail transportation asset
SUPPORT FACILITIES	1 person/175 square feet	$210/square feet	Never critical unless so designated by user
FERRIES	Maximum capacity of ferry	User input	Never critical unless so designated by user
FLEET VEHICLES	Maximum occupancy of one fleet vehicle	Average cost per vehicle x maximum number of vehicles	Never critical unless so designated by user

The CAPTool has varying data requirements depending on which asset classes are considered (see Figure 42). The user inputs each specific asset within the asset class that are critical and provides the corresponding data.

	Category							
Required Data	Road Bridges	Road Tunnels	Transit/Rail Stations	Transit/Rail Bridges	Transit/Rail Tunnels	Admin & Support Facilities	Ferries	Fleets
Identification of asset or asset class	•	•	•	•	•	•	•	•
Quantity	•	•	•	•	•	•	•	•
Annual average daily traffic	•	•						
Length (ft.)	•	•		•	•			
Travel lanes	•	•						
Detour length to nearest available crossing	•	•						
Type of construction	•			•				
Replacement cost	•	•	•	•	•	•	•	•
Maximum train capacity (occupancy)			•	•	•			
Knowledge that structure is below grade/above grade			•					
Knowledge that station is a transfer point			•					
Percentage of total ridership using the tunnel (or bridge)				•	•			
Square footage of facility						•		
Maximum occupancy of facility						•		
Maximum occupancy (persons)							•	
Maximum occupancy (vehicles)							•	•
Average cost per vehicle								•

Figure 42. List of required data for use in CAPTool (Source: FHWA (2013a))

CAPTool then provides a series of worksheet results, including: (1) which asset(s) exceed which consequence threshold for a given hazard/threat; (2) the effectiveness of countermeasures for each asset; (3) a summary page detailing the consequence thresholds, number of critical assets, and costs of countermeasures aggregated to the asset class level. CAPTool considers a range of potential countermeasure categories, including: prediction/intelligence gathering, detection, interdiction, response/preparedness, design/engineering measures. A full list of countermeasures are provided in Appendix C. Countermeasure costs are determined by using logical cost assumptions from the RSMeans cost estimating manual.[224] The user may also define additional countermeasures.

[224] The RSMeans cost manual is available at: http://www.rsmeans.com.

2-2-3 Multi-Criteria Decision-Making

FHWA partnered with Virginia DOT (VDOT) to conduct the 2010-2011 Hampton Roads Pilot for climate change vulnerability assessment in collaboration with the University of Virginia.[225] A key component of the VDOT Hampton Roads pilot study is the Multi-Criteria Decision Analysis (MCDA) model. The MCDA model helps prioritize investments for long-range transportation planning by using multiple future scenarios considering future changes in climate, economic projections, new technology, change in land use, etc. The tool requires minimal modeling or computational resources. Because it is automated and scales easily, MCDA allows for study of large networks. If these networks/structures were studied on an individual basis—rather than multi-criteria impact evaluation—they would likely result in either oversimplifying the impacts, or overlooking certain factors. MCDA is designed to handle multiple conflicting objectives and assess vulnerability for future uncertain conditions.[226] Figure 43 illustrates the structure of the MCDA developed for Virginia and tested in the HR pilot.

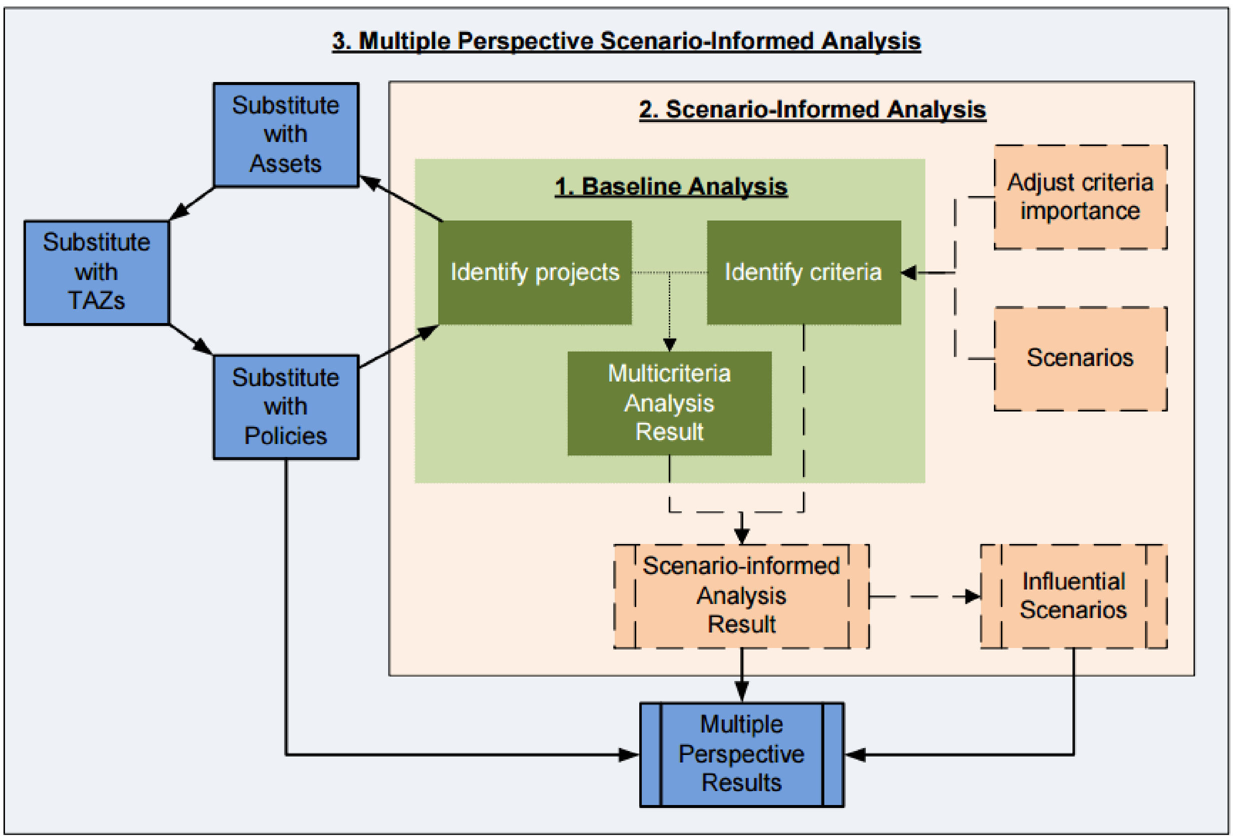

Figure 43. Structure of the Virginia model supporting the FHWA framework (Source: VDOT et al. (2012))

The Pilot methodology was driven by the priorities and infrastructure projects underway within the region. Climate change scenarios were combined with projections of economic condition, GDP growth, and maintenance/funding policies. All of these led to development of scenarios and models that were run to

[225] VDOT et al. (2012); FHWA (2011b).

[226] For research on MCDA, see: Kirshen et al. (2011).

measure the climate impacts and create new priorities for existing transportation assets, major transportation projects, transportation analysis zones (TAZs), and multimodal polices.

One tool, the MCDA, simulates how changes in transportation stressors, like climate change and the economy, may affect the prioritization of projects. Specifically, the MCDA Excel-based worksheet considers which of the HR Long-Range Transportation Projects Prioritization Criteria are affected by changes in climate (e.g., increase in SLR, increase in extreme heat days) and changes in non-climate conditions (e.g., economic recession, energy shortage). For a case study, the MCDA evaluated 155 transportation projects planned over the next thirty years. The user chooses up to five scenarios in which the user "turns on" various climate and non-climate conditions (e.g., increase in sea level rise, changes in land use regulations). The user then revisits the Prioritization Criteria and, through expert knowledge, considers how each scenario may impact the Prioritization Criteria choosing from major decrease, minor decrease, minor increase, and major increase. MCDA Tool then calculates the change in the total score for each project under each scenario.

Figure 44 shows the matrix of the scores across projects (columns). For each project, the score is provided under baseline conditions (no changes in climate and non-climate conditions) compared to changes in scores for the 5 user-defined scenarios. This provides insight as to how each scenario may influence the scoring of a given project.

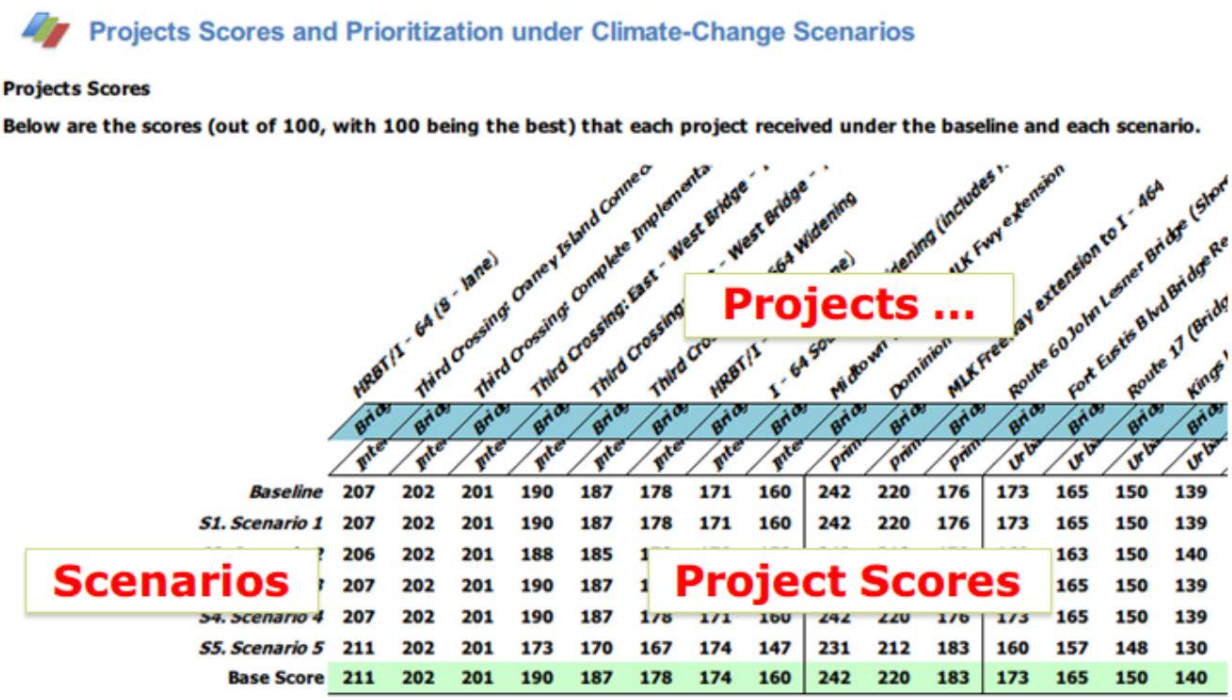

Figure 44. Matrix of the Scores for each of the climate scenarios in the FHWA MCDA assessment for Hampton Roads (Source: VDOT et al. (2012))

2-2-4 Haimes' Inoperability Input-Output/Multi-Criteria Risk-Filtering Model

This section discusses the Input-Output risk assessment and risk prioritization/filtering tool, developed by Professor Yacov Haimes and his colleagues at the University of Virginia, Center for Risk Management of Engineering Systems (CRMES) for management of climate change risks in HR and elsewhere.[227] His multi-component model serves as an overarching conceptual framework for risk assessment. This discussion is provided in this section as over a decade ago, a prototype of this model was developed for Virginia. In addition, components within this model could be considered moving forward. We were unable to locate this prototype or determine its usefulness through interviews with stakeholders; however, such efforts can continue and may produce a working model that could be adjusted for climate-related economic analysis.

The model enables researchers to integrate risk assessment and risk management through interdependent processes that involve two key analytical components:

An Input-Output Model for Estimating Regional Cost Impacts of a Disruption. The first model component calculates how a disruption to a set of transportation infrastructure and economic assets in one sector of the economy impacts other sectors and the region as a whole, due to the interdependencies among the economy's business sectors and assets. The model uses the Department of Commerce BEA data to estimate the impacts in the form of two ratios in the region subsequent to a disruption:

- The inoperability metric: defined as the normalized production loss representing the ratio of unrealized production with respect to "as-planned" production level (calculated on a scale of 0 to 100, representing the share of planned origin-destination trips disrupted, with the scale 0 representing "operations as planned," and 100 as total loss of network functionalities).
- The economic loss metric: a metric representing the value of monetary loss associated with an inoperability value. Such a loss includes reduced demand/supply for the goods and services delivered by the transportation mode/sector whose operations were disrupted, including direct and indirect loss of revenue and productivity.

Hierarchical Holographic Modeling (HHM). This model component captures the influence of the multiple dimensions of disruption reflecting the interdependencies among the sectors —power, transportation, communications, business sector, and supply chains—that influence the transportation network and operations. Risk Filtering, Ranking, and Management Method (RFRM), is a component of the HHM modeling framework that identifies, prioritizes, assesses, and manages risks to complex, large-scale systems (see adjacent textbox).

[227] Haimes (2004).

Risk filtering enables decision-makers to focus on the sources of risk that are most critical. Next the prioritized risks are further considered in the risk management (RM) phase, where potential policy options are evaluated for implementation. Finally, during the last phase of the process, the operational feedback are addressed through an iterative process of reviewing and improving the analysis derived from prior phases.

RFRM encapsulates the six questions of risk assessment and management:

- What can go wrong?
- What is the likelihood that it would go wrong?
- What are the consequences?
- What can be done? What options are available?
- What are the associated tradeoffs in terms of all costs, benefits, and risks?
- What are the impacts of current management decisions on future options?

PART 3 – NEXT STEPS IN CONDUCTING AN ECONOMIC QUANTIFICATION STUDY IN THE HR REGION

There are two key principles that guide the next steps in conducting an economic quantification regarding the transportation network in the HR region: (1) the need for national replicability; and (2) delivering value to HR stakeholders. DOT's objective for the Hampton Roads Climate Impact Initiative includes supporting a regional-scale pilot once data and methodologies are validated at the local level, through the following tasks, as follows:

- Task 2: Determining a methodology for estimating future costs using different scenarios and time scales;
- Task 3: Conducting a small-scale pilot analysis using different scenarios and time scales; and
- Task 4: Conducting a region-scale using different scenarios and time scales.

First, given DOT's role assisting states and MPOs nationwide, this Initiative will enable broader intergovernmental coordination on transportation planning, not only to bolster the quantification tools available to government, industry and the public in Hampton Roads, but eventually to other vulnerable regions nationwide. Second, DOT strives to timely add value to ongoing research efforts in the HR region through continued and sustained outreach to regional parties engaged in research on the direct and indirect impacts of SLR and storm surge on transportation networks. For example, DOT is aware of efforts including: follow on work from the HR Intergovernmental Pilot; the Joint Land Use Study funded by the Navy; and HRTPO's 2016 study on roadways, discussed in this section below. Collaboration within HR will ensure this work builds on existing efforts, while avoiding duplication. To that end, DOT continues to travel to the HR region and regularly communicate with governmental and industry representatives concerned with transportation matters.

The economic models described in this report will be evaluated, in consultation with our stakeholders, to determine which model or models is/are best suited for analysis of discrete asset components and network-wide transportation system based data availability and the indirect consequences of interest, as discussed in Part 1 of this report. Testing may include various scenarios such as the impacts associated with recurrent flooding, a baseline-event, recurrent flooding under future SLR, a future-event, a future-event accounting for potential future projects, and a future-event with a suite of adaptation measures. For instance, HRPTO developed three future coastal flood scenarios for the 2045 time-frame for potential use in their Long Range Transportation Plan that are accepted by the community and are available in GIS layers.[228] These layers could potentially serve as a jumping off point for this analysis. Examples of possible pathways for moving forward are described below:

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[228] HRTPO (2016).

- If coastal inundation from a storm event were to occur under present conditions, what are the direct and indirect economic implications associated with simulated disruptions in the transportation system for HR? Through economic impact analysis, the direct and indirect economic costs associated with study-wide transportation asset losses can be estimated. These baseline-event-impacted-assets represent a collection of assets where strategies to reduce impact could be considered as "no regrets." A present conditions analysis could answer specific questions, such as: Which economic methodology is most appropriate for this analysis? Are there specific industries most affected by transportation loss (e.g., tourism, shipping, etc.)? Are specific neighborhoods or corridors adversely affected by transportation loss that contribute to a greater loss to the economy or experience a greater loss to income? Are utilities concerned that flooded corridors will prevent them from servicing downstream customers? Are there specific transportation modes that are more greatly affected (and if so, are there interconnectivities/redundancies across modes that can compensate for this)?

- The event-driven economic analysis can be manipulated to draw out those transportation assets that are linked to the greatest potential regional costs, which can serve as an economic-based criticality tool, opposed to currently used criticality evaluation processes. Economic impact may overlap with existing criticality metrics such as redundancy where more built-in redundancy a system possesses, the less the economic consequence by loss of asset. A qualitative comparison can then be drawn as to whether this economic-based criticality tool targets different assets than would be identified through processes currently used within the HR Pilot and USDOT Gulf Coast Phase 2 study to illustrate the value-added by considering economic consequences.

- The economic impact analysis described in the first bullet could be repeated under one or more future scenarios of coastal inundation to capture additional assets, or at a broader scale, groups of assets that comprise a supply chain or strategic route for a key segment (e.g., intermodal freight shipments), that may be exposed under a changing climate and associated SLR, change in storm inundation, etc. These additional assets can be tagged with a "future-event-impacted-assets" identification (as opposed to the "currently-at-risk assets" identified in Step 1). These assets appear to function adequately under today's conditions but may not in the future due to changes in climate. Questions that could be considered: Is the economic impact analysis methodology still appropriate and robust under future scenarios? Does the future scenario economic modeling suggest significant increases in economic consequences of an equivalent event occurring under future climate conditions compared to today's conditions? Does the future scenario suggest a shift in industries or neighborhoods affected? Are there planned projects that would introduce redundancy into the system that will reduce the impact of loss of service?

- Of transportation assets that are most critical for the economic vitality of the region, what are the most cost-effective adaptation strategies? Simulated implementation of these strategies within the economic analysis would allow for an understanding of how planning could strengthen the future resilience within the region to particular types of events.

DOT may draw from its DOT Volpe Resilience Framework when conducting a full-scale analysis of the Pilot region's transportation risks and potential adoption of cost-effective mitigation and adaptation measures. The DOT Volpe risk-based framework defines resilience as the byproduct of an infrastructure system's capacity to anticipate potential risks, monitor and detect threats, adapt, reorganize and absorb damages, and respond to disturbance by mitigating the harm and restoring essential functions to ensure operational continuity (see Figure 45).[229] Embedded in the DOT Volpe Center Resilience Framework is a rigorous, proactive decision-support perspective that views risk management and adaptation planning within the context of systematic risk mitigation and portfolio-investment planning. For such a future pilot study, these adaptation components can be considered within the DOT and FHWA Framework for Vulnerability Assessment.

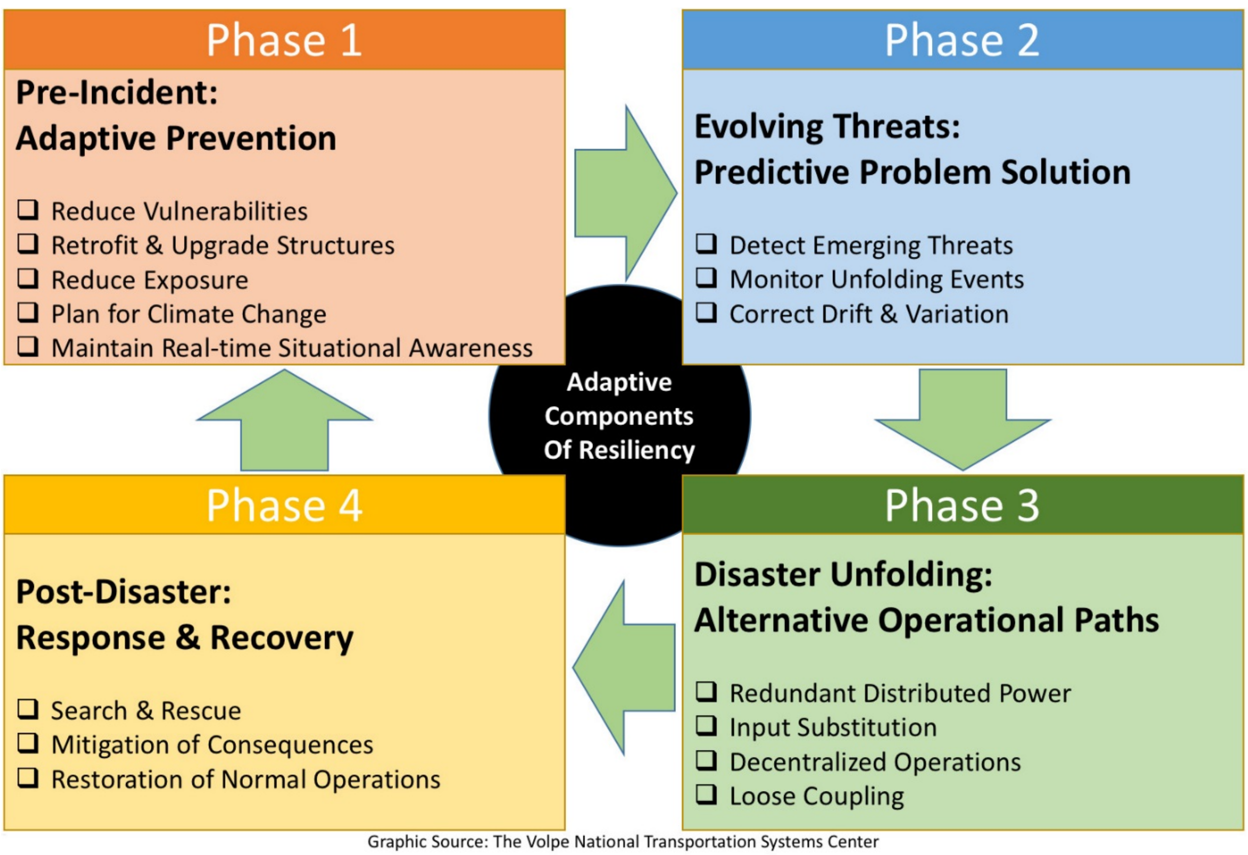

Figure 45. Adaptation components of the DOT Volpe Center Resilience Framework (Source: Volpe Center (2013)). This illustration depicts the application of adaptive measures for reducing the risks to a complex infrastructure system through a lifecycle process of preventive pre-event structural adaptation actions as well as post event mitigation measures.

[229] Volpe Center (2013).

APPENDIX A – ACRONYMS

AMS	Asset Management System
BEA	Bureau of Economic Analysis
CAPTA	Costing Asset Protection for Transportation Agencies
CASI	Climate Adaptation Science Investigator
CGE	Computable General Equilibrium
CIP	Capital Improvement Plan
CIRA	Climate Impacts and Risk Analysis
COLI	Cost of Living Index
CRMES	Center for Risk Management of Engineering Systems
DOC	Department of Commerce
DOE	Department of Energy
DOT	Department of Transportation
EIAC	Economic Impact Advisory Committee
EPA	Environmental Protection Agency
ERDC	US Army Engineers R&D Center
FAA	Federal Aviation Administration
FAF	Freight Analysis Framework
FEMA	Federal Emergency Management Administration
FHWA	Federal Highway Administration
FTZ	Foreign Trade Zone
GDP	Gross Domestic Product
GIS	Geographic Information System
GSP	Gross State Product
HAZUS-MH	Hazards United States – Multi-Hazard
HMA	Hazard Mitigation Assistance
HR	Hampton Roads
HRPDC	Hampton Roads Planning District Commission
HRTPO	Hampton Roads Transportation Planning Organization
IMPLAN	Impact Analysis for Planning
I-O	Input-Output
IPCC	Intergovernmental Panel on Climate Change
IWG	Infrastructure Working Group
LRTP	Long Term Transportation Plan
MCDA	Multi-Criteria Decision Analysis
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
NASA	National Aeronautics and Space Administration
NCADAC	National Climate Assessment and Development Advisory Committee
NCDC	National Climate Data Center

NCHRP	National Cooperative Highway Research Program
NIT	Norfolk International Terminal
NOAA	National Oceanic and Atmospheric Administration
NHC	National Hurricane Center
NNMT	Newport News Marine Terminal
NS	Norfolk Southern
NWS	National Weather Service
ODU	Old Dominion University
ORF	Norfolk International Airport
POV	Port of Virginia
R&R	Response and Recovery
REAcct	Regional Economic Accounting
RIMS II	Regional Input-Output Multiplier System
SHELDUS™	Spatial Hazard Events and Losses Database for the US
SLOSH	Sea, Lake, and Overland Surges for Hurricanes
SLR	Sea-Level Rise
SoVI	Social Vulnerability Index
SOW	Statement of Work
TAM	Transportation Asset Management
TAZ	Traffic Analysis Zone
TCC	Traffic Control Center
TEU	Twenty Foot Equivalent Unit
TMC	Traffic Management Center
VAST	Vulnerability Assessment Scoring Tool
VDOT	Virginia Department of Transportation
VIMS	Virginia Institute of Marine Science
USACE	U.S. Army Corps of Engineers
USGCRP	U.S. Global Climate Research Program

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APPENDIX C – DATA SOURCES AND DATABASE DESCRIPTIONS

Data Source	Data Obtained
HAZUS-MH	Hazards-US, Multi-hazard software (HAZUS-MH), a GIS-based loss estimation tool, uses a nationally applicable standardized methodology that estimates potential losses from earthquakes, hurricane winds and floods. The Federal Emergency Management Agency (FEMA) developed HAZUS-MH under contract with the National Institute of Building Sciences (NIBS) HAZUS-MH allows the user to map and display hazard data and the results of damage and economic loss estimates for buildings and infrastructure. It also allows users to estimate the impacts of earthquakes, hurricane winds, and floods on populations. HAZUS-MH contains valuation estimates for transportation infrastructure components. However, except for bridges it does not estimate potential damages to those components due to hazard events. https://www.fema.gov/hazus.
Spatial Hazard Events and Losses Database for the United States (SHELDUS ™)	SHELDUS is a county-level hazard data set for the U.S. and includes 18 different natural hazard events types such thunderstorms, hurricanes, floods, wildfires, and tornados. The database covers the period from January 1960 to December 2014. It contains information on the date of an event (beginning and end), affected location (county and state) and the direct losses caused by the event (property and crop losses, injuries, and fatalities). The Hazard and Vulnerability Research Institute at the University of South Carolina manages SHELDUS ™ http://hvri.geog.sc.edu/SHELDUS/. http://webra.cas.sc.edu/hvri/products/sheldusmetadata.aspx.
NOAA	In addition to meteorological data on sea level rise and flooding frequency, NOAA has also developed a range of impact estimating models and databases in its National Centers for Environmental Information (NCEI) documenting a range of climate-related events in the U.S. The storm events database currently contains data from January 1950 to September 2015, as entered by NOAA's National Weather Service (NWS). Due to changes in the data collection and processing procedures over time, there are unique periods of record available depending on the event type. http://www.ncdc.noaa.gov/. https://www.ncdc.noaa.gov/stormevents/.
USACE Data on Ports	The USACE Navigation Data Center maintains a database of over 40,000 port-and-waterway facilities and other navigation points of interest. The data describe the physical and inter-modal (infrastructure) characteristics of the coastal, Great Lakes, and inland ports of the United States. The data include, but are not limited to: location (latitude/longitude, waterway, mile, and bank); operations (name, owner, operator, purpose, handling equipment, rates, and details of open-and-covered storage facilities); type and dimension of construction (length of berthing space for vessels and/or barges, depth, apron width, deck elevation, and details of rail-and-highway access); and utilities available (water, electricity, and fire protection).USACE data on ports are available as GIS shapefiles. The point features include attributes such as dock construction type and material, owner, and use. www.navigationdatacenter.us/ports/ports.htm.

Data Source	Data Obtained
National Bridge Inventory (NBI)	The NBI contains codes for over 130 items related to bridges. It includes identifying information, structural information, condition information, usage information, and more. The data are available at the FHWA website, as is the coding guide that explains what is being rated and what the codes mean. Some of the items used in the report include structure type, average daily traffic, scour rating, and deck condition. http://www.fhwa.dot.gov/bridge/nbi.cfm. http://www.fhwa.dot.gov/bridge/mtguide.pdf.
National Transportation Atlas Database (NTAD)	The NTAD is a set of nationwide geographic databases of transportation facilities, transportation networks, and associated infrastructure. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_atlas_database/index.html.

APPENDIX D – SUPPORTING INFORMATION AND TERMINOLOGY

HRTPO Prioritization Tool and Scoring Criteria for Economic Vitality[230]

Highway projects:

ECONOMIC VITALITY	
Total Reduction in Travel Time	**30.00**
Labor Market Access	**20.00**
Increase Travel Time Reliability	*10.00*
Increased Access for High Density Employment Areas	*10.00*
Addresses the Needs of Basic Sector Industries	**30.00**
Increases Access for Port Facilities	*10.00*
Increases Access to Tourist Destinations	*10.00*
Increases Access for Defense Installations	*6.00*
Facility part of STRAHNET	*4.00*
Facility part of "Roadways Serving the Military"	*3.00*
Increased Opportunity	**20.00**
Provides New of Increased Access	*10.00*
Supports Plans for Future Growth	*10.00*
ECONOMIC VITALITY TOTAL	***100.00***

Interchange projects:

ECONOMIC VITALITY	
Total Reduction in Travel Time	**30.00**
Labor Market Access	**20.00**
Increase Travel Time Reliability	*10.00*
Increased Access for High Density Employment Areas	*10.00*
Addresses the Needs of Basic Sector Industries	**30.00**
Increases Access for Port Facilities	*10.00*
Increases Access to Tourist Destinations	*10.00*
Increases Access for Defense Installations	*6.00*
Facility part of STRAHNET	*4.00*
Facility part of "Roadways Serving the Military"	*3.00*
Increased Opportunity	**20.00**
Provides New of Increased Access	*10.00*
Supports Plans for Future Growth	*10.00*
ECONOMIC VITALITY TOTAL	***100.00***

[230] HRTPO (2013c).

Bridge and tunnel projects:

ECONOMIC VITALITY	
Total Reduction in Travel Time	**30.00**
Labor Market Access	**20.00**
Increase Travel Time Reliability	*10.00*
Increased Access for High Density Employment Areas	*10.00*
Addresses the Needs of Basic Sector Industries	**30.00**
Increases Access for Port Facilities	*10.00*
Increases Access to Tourist Destinations	*10.00*
Increases Access for Defense Installations	*6.00*
Facility part of STRAHNET	*4.00*
Facility part of "Roadways Serving the Military"	*3.00*
Increased Opportunity	**20.00**
Provides New of Increased Access	*10.00*
Supports Plans for Future Growth	*10.00*
ECONOMIC VITALITY TOTAL	***100.00***

Transit projects:

ECONOMIC VITALITY	
Labor Market Access	**45.00**
Increases Access for Major Employment Centers	***20.00***
Increases Travel Time Reliability	***10.00***
Increases Frequency of Service	***10.00***
Provides Access to Institutions of Higher Education	***5.00***
Addresses the Needs of Basic Sector Industries	**20.00**
Provides or Improves Access for Defense Installations	***10.00***
Provides/Improves Access for Tourist Destinations	***10.00***
Increased Opportunity - Provides New Access to the Network	**20.00**
Provides New Access to the Network	***5.00***
Supported by Plans for Increased Density and Economic Activity	***15.00***
Economic Distress Factors	**15.00**
Provides Access to Areas with High Unemployment	***5.00***
Provides Access to Low Income Areas	***10.00***
ECONOMIC VITALITY TOTAL	***100.00***

Intermodal projects:

ECONOMIC VITALITY	
Total Reduction in Travel Time	**20.00**
Labor Market Access	**35.00**
Increase Travel Time Reliability	*15.00*
Impact on Truck Movement	*15.00*
Increased Access for High Density Employment Areas	*5.00*
Addresses the Needs of Basic Sector Industries	**15.00**
Increases Access for Port Facilities	*5.00*
Improves Flow of Rail	*5.00*
Increases Access to Air	*5.00*
Increased Opportunity	**30.00**
Provides New of Increased Access	*20.00*
Supports Plans for Future Growth	*10.00*
ECONOMIC VITALITY TOTAL	***100.00***

HAZUS-MH Valuation Formulas

Table 3.21 Highway System Classifications

Flood Label	General Occupancy	Specific Occupancy	Hazus Valuation[1]
HRD1	Highway Roads	Major Roads (1km 4 lanes))	10,000
HRD2	Highway Roads	Urban Roads (1 km 2 lanes)	5,000
HTU	Highway Tunnel	Highway Tunnel	20,000
HWBM	Highway Bridge	Major Bridge	20,000
HWBO	Highway Bridge	Other Bridge (include all wood)	1,000
HWBCO	Highway Bridge	Other Concrete Bridge	1,000
HWBCC	Highway Bridge	Continuous Concrete Bridge	5,000
HWBSO	Highway Bridge	Other Steel Bridge	1,000
HWBSC	Highway Bridge	Continuous Steel Bridge	5,000

Notes:

1 *All dollar amounts are in thousands of dollars.*

Table 3.22 Railway System Classifications

Flood Label	General Occupancy	Specific Occupancy	Hazus Valuation[1]
RTR	Railway Tracks	Railway Tracks (per km)	1,500
RBRU	Railway Bridge	Railway Bridge Unknown	5,000
RBRC	Railway Bridge	Concrete Railway Bridge	5,000
RBRS	Railway Bridge	Steel Railway Bridge	5,000
RBRW	Railway Bridge	Wood Railway Bridge	5,000
RTU	Railway Tunnel	Railway Tunnel	10,000
RSTS	Railway Urban Station	Steel Railway Urban Station	2,000
RSTC	Railway Urban Station	Concrete Railway Urban Station	2,000
RSTW	Railway Urban Station	Wood Railway Urban Station	2,000
RSTB	Railway Urban Station	Brick Railway Urban Station	2,000
RFF	Railway Fuel Facility	Railway Fuel Facility (Tanks)	3,000
RDF	Railway Dispatch Facility	Railway Dispatch Facility (Equip)	3,000
RMFS	Railway Maintenance Facility	Steel Railway Maintenance Facility	2,800
RMFC	Railway Maintenance Facility	Concrete Railway Maintenance Facility	2,800
RMFW	Railway Maintenance Facility	Wood Railway Maintenance Facility	2,800
RMFB	Railway Maintenance Facility	Brick Railway Maintenance Facility	2,800

Notes:

1 All dollar amounts are in thousands of dollars.

Bridge Standards Discussed in this Report

Functionally Obsolete: a structure that was built to geometric standards that are no longer used today. These bridges do not have adequate lane width, shoulder width, or vertical clearances to serve the current traffic volumes or meet current geometric stands. These bridges may be more likely to be occasionally flooded or have approaches that are difficult to navigate. However, they are not inherently unsafe.

Structurally Deficient Bridges: Bridges are structurally deficient when one or more major components is deteriorating. Structurally deficient bridges need to be monitored or repaired, but are not necessarily unsafe. Transportation agencies will close unsafe bridges.

Deficient Bridges: Defined as the combination of structurally deficient and functionally obsolete bridges. This category has historically been used to determine eligibility for federal funding. [Combines Structural and Functional deficiency]

Weight-posted Bridges: These bridges are defined as structures that have a rated load-carrying capacity that is less than the designated legal truck weights in the state of VA (where the maximum legal truck weigh is 27 tons for a 3-axle single unit vehicle and 40 tons for trucks with semi-trailers. A total of 102 bridges in HR (8.3%) have posted weight restrictions, ranking 11th among comparable metro areas.

Fracture and Scour Critical Bridges: Two types of structure require more monitoring than typical bridges due to their design or location: Fracture Critical structures and bridges that are Vulnerable to Scouring. Most bridges are designed so that loads of can be redistributed to other structural members if any one structural member loses its ability to distribute loads. However, fracture critical bridges are structures that are designed with few or no redundant supporting elements and are in danger of collapsing if a key structural member fails. Despite this lack of redundancy, however, fracture critical bridges are not necessarily unsafe. They, however, undergo more extensive and more frequent inspections, usually on an annual basis. Examples of FC bridges are most truss bridges, drawbridges, and those beam or girder bridges designed without redundant elements.

Scour Critical Bridges: Bridges with underwater substructure sections may be vulnerable to scouring, i.e., the exposure of portions of the substructure due to changes in the riverbed. In cases where a bridge is a risk of failure due to scouring, they are inspected more frequently (every 5 years) to assure that the potentially vulnerable ones do not in fact become scour critical. Currently no bridges in HR are classified as such.

Table D-1. Scour Critical Bridges codes (Source: *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*)

Code	Description
N	Bridge not over waterway.
U	Bridge with "unknown" foundation that has not been evaluated for scour. Since risk cannot be determined, flag for monitoring during flood events and, if appropriate, closure.
T	Bridge over "tidal" waters that has not been evaluated for scour, but considered low risk. Bridge will be monitored with regular inspection cycle and with appropriate underwater inspections. **("Unknown" foundations in "tidal" waters should be coded U.)**
9	Bridge foundations (including piles) on dry land well above flood water elevations.
8	**Bridge foundations determined to be stable for assessed or calculated scour conditions; calculated scour is above top of footing.**
7	Countermeasures have been installed to correct a previously existing problem with scour. Bridge is no longer scour critical.
6	Scour calculation/evaluation has not been made. (Use only to describe case where bridge has not yet been evaluated for scour potential.)
5	**Bridge foundations determined to be stable for calculated scour conditions; scour within limits of footing or piles.**
4	**Bridge foundations determined to be stable for calculated scour conditions; field review indicates action is required to protect exposed foundations from effects of additional erosion and corrosion.**
3	Bridge is scour critical; bridge foundations determined to be unstable for calculated scour conditions: - Scour within limits of footing or piles. - Scour below spread-footing base or pile tips.
2	**Bridge is scour critical; field review indicates that extensive scour has occurred at bridge foundations. Immediate action is required to provide scour countermeasures.**
1	Bridge is scour critical; field review indicates that failure of piers/abutments is imminent. Bridge is closed to traffic.
0	**Bridge is scour critical. Bridge has failed and is closed to traffic.**

Table D-2. Countermeasure costs for each countermeasure "hard-wired" into the CAPTool (source: CAPTool spreadsheet)

Countermeasure Category	Countermeasure	ESTIMATED PER-UNIT COST (x1000)	Comments	Unit of measure
Physical Security Countermeasures	Lighting	11.3	one per 100 feet of road or perimeter. Assumes nearby power connection, no demolition or excavating.	1
	Barriers & Berms	3.3	10 jersey barriers and two end planters to cover 100 feet of space	1
	Fences	21	12 foot height security fence, in concrete with 4 gates (6 feet high, 3 feet wide). Infrared detection system. Power install, relay to central monitor. Excludes central monitoring station operation.	100 linear feet
	CCTV	17.5	4 remote PTZ cameras, one control panel	1
	Intrusion Detection Devices	0.9	1 burglar alarm with remote signal installed	1
	Physical Inspection of asset	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE employee per year
Access Control Countermeasures	ID Cards	10	6 zone system with database, installed	6 zones
	Biometrics	50	6 facial and fingerprint scanners, database, installed	6 zones
	Background Checks	57	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Metal Detectors	138	6 portals, 4 handhelds, installed. Assumes no demolition and nearby power source	
	Restricted Parking	18.45	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Random Inspections	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Visible Badges	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Limited Access Points	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Visitor Control & Escort	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Locks	1.2	1 cipher lockset, installed. Assumes no demolition or heavy construction	Each
	Explosive Detection	257	2 portals, 2 handhelds, with power	2+2
	Establish Clear Zones	0.1	100 sq yards. Assumes no demolition	100-SY
	Visible Signs	0.09	1 aluminum sign 18 inches high, with base	Each
Asset Design/Engineering	Seismic Retrofitting	10000	Estimates must be changed to reflect local variation	Per application
	Fire Detection & Supression	459.992	Class III standpipe system with Type 2 water supply to 10,000 sf building. System includes minimum 20 pull stations with master box, annunciator, and central station relay. Assumes minimal demolition.	
	Encasement, Wrapping, Jacketing	0.6	Estimates must be changed to reflect local variation	100-SF
Operational Countermeasures	Patrols	30	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	WX/Seismic Information	100	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	Intelligence Networking	100	1 full time equivalent (FTE) contract employee dedicated to this task	1 FTE contract employee per year
	HAZMAT Mitigation	1329.6	Assumes complete start up of hazmat remediation program providing 24 hour coverage. Mechanized crew of 8 persons. Excludes material dumping costs	1crew
	Security Awareness Training	100	Contracted	1 program
	Emergency Response Training	100	Contracted	1 program
	Emergency Evacuation Planning	100	Designed program for structures and stations	1 program
	Planned Redundancy (e.g., detours)	220	Pre-staged and marked detours. Deploys one FT traffic engineer, 1 PT carpenter, 1 PT operating engineer,	$9,000 fixed cost - $211,000 per year
	Public Information and Dissemination	150	1 PIO, 1 web technician.	2 FT employee per year

HRPDC Asset Value Methodology

The HRPDC methodology for estimating the number of businesses impacted by SLR risks was based on the individual businesses' location data collected from ESRI's Business Analysis suite. This business layer was spatially joined to a locality boundary layer to give business a county/city identifier. The data layer was overlaid on top of each SLR vulnerability zone. The total number of businesses and employees was calculated for each scenario for all 16 HR localities and the region as a whole. Parcel information was also used to represent the economic impact: i.e., the total value of each parcel as representing investments in real property.[231]

Two key metrics in the 2012 Phase III HRPDC report are helpful for estimating the economic impacts of the potential damages to the transportation infrastructure: the “Improvement Value” of the parcels within the region’s “Built Environment” and the “Total value of the parcels.” Improvement values are the value of buildings and other non-land improvements on those properties (a measure of how much “immovable” property is exposed). While improvement value indicates how much has been built at a given location, total value indicates the market value of the whole property. In many vulnerable areas, land values are higher than improvement values, since waterfront property is highly desirable.

VAST Tables of Sensitivity and Adaptive Capacity

Table D-3. List of sensitivity indicators provided in the sensitivity indicator library (Source: VAST Tool)

Roads	Bridges	Rail lines	Ports	Airports	Transit
Temperature					
- Past Experience with temperature - Truck Traffic - Temperature Threshold in Pavement Binder - Thermal Expansion Coefficient of Concrete - Condition of Concrete Pavement Joints - Presence of Bus Routes - Use of Polymer Modified Binders	- Past Experience with temperature - Truck Traffic - Temperature Threshold in Pavement Binder - Thermal Expansion Coefficient of Concrete - Condition of Concrete Pavement Joints - Presence of Bus Routes - Use of Polymer Modified Binders	- Past Experience with Temperature - Rail Design - Maintenance Frequency - Ballast Type - Shade - Rail-neutral Temperature - Rail Curvature - Permafrost	- Past Experience with Temperature - Size of Paved Asphalt Areas - Reliance on Electrical Power - Materials Handled - Frequency of Breaks - Safety Regulation Threshold	- Past Experience with Temperature - Runway Surface Pavement Type - Runway Condition - Runway Length - Airport Elevation - Thermal Expansion Coefficient of the Concrete - Condition of Concrete Pavement Joints - Use of Warm-Mix Asphalt - Use of Polymer Modified Binders	- Past Experience with Temperature - Age of Buses

231 (Note: HRPDC III does not include shoreline and flood protection infrastructure; to this extent, the results may best be interpreted as general baseline estimates of SLR in the absence of adaptation measures.)

Heavy Precipitation					
- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Proximity to Coast	- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Approach Elevation - Bridge Age - Scour Rating - Channel Condition - Culvert Condition - Frequency that Water Overtops Bridge - Proximity to Coast	- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Undercut Track - Ballast Type - Electric Signals - Soil Type - Maintenance Frequency - Condition of Drainage System - Materials Used in Drainage System - Design Capacity of Drainage System - Age of Drainage System	- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Age of Wharves, Structures - Materials Handled - Sediment Buildup - Materials Sensitive to Freezing - Condition of Drainage System - Design Capacity of Drainage System	- Past Experience with Precipitation - Age of Drainage System - Drainage System Pipe Condition - Evidence of Blowouts - Propensity for Ponding - Percentage of Impervious Surface - Airport Traffic/Congestion Levels - Soil Type - Runway Condition - Surface Treatment - Approach Lights - Instrumentation Type	- Past Experience with Precipitation - Propensity for Ponding - Percentage of Impervious Surface - Impaired Assets - Ventilation/ Tunnel Openings in Flood-Prone Areas - Flood Protection
Sea Level Rise					
- Past Experience with Tides/SLR - Flood Protection - Soil Type - Nearby Areas Exposed to SLR	- Past Experience with Tides/SLR - Approach Elevation - Navigational Clearance of Bridge - Bridge Height - Soil Type - Nearby Areas Exposed to SLR	- Past Experience with Tides/SLR - Drainage System Performance - Elevation - Soil Type - Protection	- Past Experience with Tides/SLR - Shoreline Protection - Age of Wharves, Structures - Elevation Relative to Sea Level - Height of Drainage Outlets Relative to Sea Level - Floating or Fixed - Type of Operations	- Past Experience with Tides/SLR - Height of Drainage Discharge - Drainage System Pipe Condition - Evidence of Blowouts - Age of Drainage System - Adjacent to Areas Exposed to Sea Level Rise - Access Roads Vulnerable to Sea Level Rise	- Past Experience with Tides/SLR - Elevated or Protected above Bare Earth Elevation - Impaired Access - Ventilation/ Tunnel Openings in Flood-Prone Areas - Flood Protection

Storm Surge					
- Past Experience with Storm Surge Flood Protection - Elevation of Asset	- Past Experience with Storm Surge - Bridge Height - Navigational Clearance of Bridge - Scour Rating - Condition of Bridge Substructure - Condition of Bridge Superstructure - Condition of Bridge Deck - Movable Bridge - Bridge Age - Approach Elevation - Elevation of Asset - Weight of Bridge Deck - Bridge Deck Type - Number of Longitudinal Girders	- Past Experience with Storm Surge - Drainage System Performance - Elevation or Protection - Undercut Track - Ballast Type - Soil Type - Electric Signals - Elevation of Asset - Materials Used in Drainage System - Design Capacity of Drainage System	- Past Experience with Storm Surge - Shoreline Protection - Height of Key Infrastructure - Age of Wharves, Structures - Condition - Reliance on Electrical Power - Materials Handled - Types of Key Infrastructure - Location of Key Equipment	- Past Experience with Storm Surge - Foundation Type - Drainage System Pipe Condition - Age of Drainage System - Evidence of Blowouts - Soil Type - Approach Lights	- Past Experience with Storm Surge - Foundation Type - Elevated or Protected above Bare Earth Elevation - Impaired Access - Ventilation/ Tunnel Openings in Flood-Prone Areas - Flood Protection
Wind					
- Past Experience with Wind - Roadway Signal Density - Wind Design Speeds - Proximity of Trees to Power Lines - Efficacy of Tree Trimming Maintenance - Building Density - Presence of Overhead Utility Lines - Sign Support Strength - Height and Size of Road Signs - Length of Support Arms	- Past Experience with Wind - Roadway Signal Density - Wind Design Speeds - Proximity of Trees to Power Lines - Efficacy of Tree Trimming Maintenance - Building Density - Presence of Overhead Utility Lines - Sign Support Strength - Height and Size of Road Signs - Length of Support Arms - Fixed of Cabled Signals?	- Past Experience with Wind - Number of Signals/Signs or Major Crossings - Presence of Ariel Signal Lines - Proximity of Trees to Power Lines - Efficacy of Tree Trimming Maintenance - Building Density - Presence of Overhead Utility Lines - Sign Support Strength - Height and Size of Road Signs - Length of Support Arms	- Past Experience with Wind - Age of Wharves, Structures - Reliance on Electrical Power - Materials Handled - Wind Design Speeds - Port Equipment - Nearby At-Risk Infrastructure	- Past Experience with Wind - Age of Buildings - Building Material Type - Roof Type - Height of Air Traffic Control Tower - Height of Hangers - Height of Terminals - Sheltered by Surrounding - Wind Design Speeds Operations - Proximity to Projectile Materials	- Past Experience with Wind - Age of Buildings or Fleet - Building Material Type - Roof Type - Building Height - Sheltered by Surrounding Structures - Wind Design Speeds

- Fixed of Cabled Signals? - Underground or Overhead Power and Utilities?	- Underground or Overhead Power and Utilities?	- Fixed of Cabled Signals? - Underground or Overhead Power and Utilities?			

Table D-4. List of sensitivity indicators provided in the adaptive capacity indicator library (Source: VAST Tool)

Roads	Bridges	Rail lines	Ports	Airports	Transit
Replacement Cost	Replacement Cost	Presence of Bridges along Segment	Redundancy within a Facility	Special Designation	Priority for Assistance
Detour Length	Detour Length	Signaling	Redundancy across Facilities	Number of Terminals	Function or Facility Asset
Disruption Duration	Disruption Duration	Evacuation Plans	Disruption Duration	Number of Runway Headings	Disruption Duration
FHWA Roadway Functional Classification	FHWA Roadway Functional Classification	Part of Disaster Relief Recovery Plan	Availability of Supplies and Repair Equipment	Distance to Nearest Alternate Airport	Ability to Reroute
Evacuation Route	Evacuation Route	Ability to Reroute System	Sharing Equipment across Ports, Agencies	Number of Alternate Airports within 120 Miles	Ability of Fixed Lines to Reroute
Annual Average Daily Traffic	Annual Average Daily Traffic	Interchange Utility	Cost of Replacement of Specific Assets	Disruption Duration	Ability to Reroute around Problem Areas
Historical Repair Cost	Historical Repair Cost	Disruption Duration	Historical Cost of Replacement	Cost of Replacement of Specific Assets	Cost of Replacement of Specific Assets

Access to Critical Areas	Access to Critical Areas	Replacement Cost	Usage Statistics	Historical Cost of Replacement	Historical Cost of Replacement
		Number of Rail Lines	Access to Critical Areas	Usage Statistics	
			Tourism Costs	Access to Critical Areas	
			Cost of Disrupted or Increased Shipping Routes	Redundancy in Power Systems	
				Tourism Costs	
				Cost of Disrupted or Increased Shipping Routes	

APPENDIX E – MERGING INSURANCE "KNOW-HOW" WITH TRADITIONAL CLIMATE-RELATED RISK ASSESSMENTS TO QUANTIFY ECONOMIC LOSS

Insurance providers routinely assess financial risk of weather-related events for insurance policies and financial investments. Some of the methodologies and strategies for considering risk management may be transferable and/or informative when considering methodologies for quantifying economic costs associated with event driven impacts on transportation. A sampling of possibilities are presented below as provided by Mr. Steven Kolk* through an interview.

Actuaries Climate Indices (ACI). The Actuaries' Climate Index (ACI) (see: ActuariesClimateIndex.org.) quantifies the change in the frequency of extreme climate from a combination of a handful of extreme events relative to natural variability (i.e., is the change in extremes statistically different that than suggested by past records). The ACI is an overall index from a combination of a handful of component indexes. An example of an ACI index component is the change in monthly high temperatures compared to the historic 90th percentile of monthly high temperatures (i.e., a very hot month). Another example is the Sea Level ACI component which uses tide gauge data to calculate the effective change in sea level compared to the baseline. The overall ACI and its component indices are useful in showing how the frequency of extreme climate-related events have changed over time for a given location (e.g., have heavy precipitation events increased). For estimates of future exposure to climate risk, the ACI could be extended by post-processing and forecasting the climate index components.

Looking at history there does appear to be overlap between ACIs and climate indices used in hazard assessments. For example, the ACI for flooding is the 5-day maximum precipitation event, which is also one of the indices used to indicate future changes in flooding by the climate community.

Mr. Kolk conducted a correlation analysis of ACI index components for Hampton Roads as shown in the table below from 1991 to 2013. There is a strong positive correlation between monthly high temperatures and sea level rise and a strong negative correlation between wind power and sea level rise. This suggests that from 1991 to 2013, the increasingly more frequent hot months have been increasing at a rate somewhat similar to sea level rise. Also, perhaps like a fan blowing wind cools a room in your apartment or home on a hot summer day, the warmer rising seas (again for the 1991 to 2013 period) may be evaporating more moisture into the air and disbursing sea power (hence the negative correlation) most especially when the more extreme winds are blowing. These types of correlations may also be helpful when considering if these climate indices could occur simultaneously - which could potentially compound the realized impacts.

Actuarial Aspects. When considering climate risks, there are a number of actuarial aspects to consider, and more research could help. Facts to bring to bear and consider could be, determining location-specific exposure and sensitivity to coastal inundation from sea level rise. Sensitivity of coastal areas to sea level rise and water inundation will be dependent on such elements as the coastline's slope, aspect (or direction of the slope), state of erosion, and topography. These elements overlap with those identified by the climate community when conducting climate-risk based hazard assessments; in other words, the insurance industry likely considers the same elements of risk as the climate/hazard assessment community. When considering property damage, Actuaries Climate Risk Index (ACRI) modeling further suggests population is a significant factor explaining SHELDUS damages. Actuaries who build such models work together with a scientists as NOAA who gather and share data, and risk experts.

Table E-1. ACI Component Correlations with the ACI Sea-Level Rise Index from 1991 to 2012

ACI Component Correlations with the ACI Sea-Level Rise Index from 1991 thru 2013								10-Yr Moving Avg. Correlation	
	Lengthy Drought	Heavy Precipitation	**Sea Level Rise**	Soil Moisture	Low Temperatures	High Temperatures	Wind Power	Average Correlation Coefficient	Standard Dev'n of Corr. Coef.
Lengthy Drought	1.000	-0.535	0.140	-0.800	-0.522	0.495	-0.351	-0.779	0.030
Heavy Precipitation	-0.535	1.000	-0.044	0.687	0.430	-0.345	0.271	0.181	0.279
Sea Level Rise	0.140	-0.044	1.000	-0.567	-0.602	0.720	-0.894	1.000	0.000
Soil Moisture	-0.800	0.687	-0.567	1.000	0.681	-0.774	0.720	-0.163	0.058
Low Temperatures	-0.522	0.430	-0.602	0.681	1.000	-0.745	0.751	-0.142	0.456
High Temperatures	0.495	-0.345	0.720	-0.774	-0.745	1.000	-0.811	**0.797**	**0.094**
Wind Power	-0.351	0.271	-0.894	0.720	0.751	-0.811	1.000	**-0.895**	**0.036**

Modeling the Consequences of Climate-Related Events. Insurers use a variety of risk modelers (AIR, ARA, EQECAT and RMS) to build risk modelers of many kinds. These models, like FEMA's HAZUS, estimate damage to buildings from Hurricanes, Storm Surge and Flooding. These models provide estimate of risk in terms of the Average Annual Loss (AAL) (i.e., the expected annual loss per year) and Probable Maximum Loss (PML) (i.e., the largest loss that may occur under a disaster/event) associated with personal and commercial property loss. These kinds of estimates could be used to quantify and rank the exposure of various properties exposed to SLR risk. When such models are built, they most often quantify just the short-term direct impacts of individual events. Modeling firms have begun to apply their modeling skills to also estimate the costs of the indirect aftermath from power recovery costs, business interruption and supply chain delays following bigger events. Both kinds of information may be useful, for example, in the CAPTA tool. This then could identify those populations at greatest risk to consider socioeconomic consequences if these populations whose properties are at greater risk to get flooded are also stranded by loss of transportation services/passable facilities.

A few firms have begun to collect additional information to quantify the indirect consequences of transportation disruption.

* Steve Kolk, ACAS, MAAA, Assistant Vice President of Pricing, American Integrity Insurance Company of Florida

APPENDIX F— LETTER FROM CAPTAIN D.A. VANDERLAY, U.S. NAVY, COMMANDING OFFER, NAVAL FACILITIES ENGINEERING COMMAND, NORFOLK, VA TO ALASDAIR CAIN, CO-CHAIR, U.S. DOT CLIMATE CHANGE CENTER (JULY 1 2016)

DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND, MID-ATLANTIC
9324 VIRGINIA AVENUE
NORFOLK, VA 23511-3095

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JUL 0 1 2016

Alasdair Cain
Co-Chair, U.S. DOT Climate Change Center,
Office of the Secretary of Transportation (OST-R)
1200 New Jersey Avenue SE, Room E33-304,
Washington, DC 20590

Dear Mr. Cain,

SUBJECT: DEPARTMENT OF TRANSPORTATION'S DRAFT HAMPTON ROADS CLIMATE IMPACT QUANTIFICATION INITIATIVE STUDY

Thank you for the opportunity for our agency to provide comments on the draft U.S. Department of Transportation's Hampton Roads Climate Impact Quantification Initiative Scoping Paper and Preliminary Baseline Assessment. The scope of the quantification study is comprehensive and starts to address the transportation and economic risks that the Hampton Roads community faces on a regular basis from recurrent flooding, storm surge, and rising seas. The quantification of these impacts, as demonstrated by the baseline assessment, will ultimately serve as a valuable resource for local, regional, and federal agencies, including the Navy, in developing strategies to mitigate and adapt to these emerging risks. In particular, the study will serve as a resource for the both of the region's two upcoming Joint Land Use Studies (JLUS): Norfolk/Virginia Beach and Portsmouth/Chesapeake.

As part of our review of the baseline assessment, we offer a correction to the population figures listed in the chart included in Section 4-3 "Quantifying the Economic Impacts of SLR on the HR Military and Transportation Sectors: Norfolk Area Military Facilities". Please see below for our corrected population figures:

Norfolk Area Military Facilities	Active Duty FY15	Reserves FY15	Civilian FY15	Contractors FY15
NS Norfolk	42997	1462	13438	7037
JEBLCFS	10422	4547	3222	723
NAS Oceana/Dam Neck	9724	980	2786	3080
NNSY	804	96	9921	1553
NWS Yorktown	1379	186	1103	453
NSA Hampton Roads	6942	445	3266	456
Total for Hampton Roads	**72268**	**7716**	**33736**	**13302**

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Again, we appreciate the opportunity to participate in the review of this important initial effort and look forward to collaborating with US DOT as we move forward with the JLUS projects and other initiatives addressing recurrent flooding. If you have any questions regarding our comments or on future collaboration, please contact Brian Ballard, Regional Community Plans and Liaison Officer, at (757) 341-0264 or brian.p.ballard@navy.mil.

Sincerely,

D. A. VANDERLEY
Captain, Civil Engineer Corps
U. S. Navy
Commanding Officer