Hampton Roads Climate Impact Quantification Initiative:

Scoping Paper and Preliminary Baseline Assessment of the Transportation Assets in Hampton Roads

Task 1a

DRAFT

May 6, 2016

U.S. Department of Transportation
Research and Innovative Technology Administration
John A. Volpe National Transportation Systems Center

Notice

This document is disseminated under the sponsorship of the U.S. Department of Transportation in the interest of information exchange. The U.S. Government assumes no liability for use of the information contained in this document. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trademarks or manufacturers' names appear herein only because they are considered essential to the objective of this document.

DRAFT

Executive Summary 6
Introduction 8
1 – Hampton Roads Pilot: Study Approach and Region's Geography 9
1-1 Study Approach and Pilot Participants 9
Pilot Participants and Steering Committee 11
Data Sources 11
1-2 Hampton Roads: The Region's Geography, Economy, and Demographics 12
Geography of Hampton Roads and the Pilot Region 12
Incomes, Jobs and Employment Sectors 13
2 – Hampton Roads: The Multimodal Transportation Network 16
Roads 17
Bridges 18
Tunnels 24
Railroads 27
Airports 32
Sea Ports 34
Pipelines 37
3 – Hampton Roads Climate Stressors and Approaches to Quantifying Exposure and Damage Consequences 40
3-1 Climate Stressors 41
3-2 Quantifying the Consequences: Conventional Methods for Measuring the Impacts of Climate Events 46
Measuring Transportation Costs of Adverse Events 47
Using the EIA Methodology to Evaluate Consequences of Transportation Projects or Events 49
Measuring Economic Impacts of Transportation through I-O Models 50
3-3 Tools for Managing Transportation Assets and Addressing Economic Impacts of Climate Change 51
Transportation Asset Management (TAM) 51

DRAFT

The NCHRP CAPTA/CAPTool: A Consequence-Based Risk Management Tool 53

3-4 Federal Processes and Templates for Streamlining Assessment of Transportation Infrastructure Risks 55

USACE Infrastructure Risk Management Tools 56

FHWA/VDOT Process for Conducting Regional Risk Assessment 59

The VAST Tool 61

EPA's Climate Impacts and Risk Analysis (CIRA) Tool 70

NOAA's Climate Adaptation Tools: Coastal Resilience Index and Social Vulnerability Index 70

NASA's Climate Adaptation Science Investigator (CASI) Tool 70

4 – Preliminary Estimates of the Costs and Exposure Levels of Norfolk/HR Region Transportation Infrastructure 71

4-1 Historical Damage Data for Floods and Hurricanes 71

SHELDUS Data 71

NOAA Storm Event Database of Losses 73

4-2 Determining Transportation Asset Value: Data on Potential Scale of Infrastructure Damage Costs 73

HRPDC Infrastructure and Property Loss Damage Estimates 73

Sandia's Estimates of Direct and Indirect Economic Impacts of Flooding Risks in Norfolk .. 76

4-3 Quantifying the Economic Impacts of SLR on the HR Military and Transportation Sectors 79

Economic Impacts of the Military Sector 79

Aviation: Climate Risks and Economic Impacts 82

Seaports: Regional Economic Impacts 83

4-4 Quantifying the Full Costs of SLR and Flooding: Costs of Business Interruption, Loss-of-Use, and Loss-of-Income 85

The Indirect Cost Burden of Repetitive Losses and Uncompensated Damages 86

Norfolk's Poverty Rate: Influence of Social Vulnerabilities 87

Availability of Private Insurance: Addressing the Public-Goods Character of Many Climate Events 91

5 – Adaptation: Decision Models and Selection of Candidate Projects 92

5-1 Adaptation Process and Alternative Measures 93

NOAA Evaluation Template 94
The FHWA Pilot 11-Step Adaptation Process 96
New York City's Pre-Sandy Adaptation Framework 97
The City of Norfolk Candidate Adaptation Projects 99
6 – Scoping the Boundaries of the Future Tasks 104
Appendix A – Acronyms 107
Appendix B – References 109
Appendix C – Data Sources and Database Descriptions 113
Appendix D – Economic Analysis Tools 118

DRAFT

Executive Summary

The DOT Climate Impact Quantification Initiative study is a baseline assessment of the economic impacts of climate-related disruptions on the Hampton Roads (HR) region and its transportation infrastructure. This assessment has a two-faceted focus, one on the HR region as a whole, and another narrowed down to the Norfolk and Pretty Lake Pilot areas, to the extent downscaled data have been available. The Pretty Lake neighborhood is located in both Norfolk and Virginia Beach. This study supports a broader effort by the HR Sea Level Rise Preparedness and Resilience Intergovernmental Pilot Project (IPP HR Pilot) convened by Old Dominion University (ODU), under the guidance of a Steering Committee, including Federal Liaisons, an Infrastructure Working Group (IWG), and an Economic Impacts Advisory Committee (EIAC). While this study focuses on quantification of transportation impacts, it also acknowledges the interdependency of the transportation network with the broader regional economy and other critical assets in the region, including the energy sector, the military assets, and the regional emergency response capabilities. It should be noted that this HR pilot is unrelated to the 2012 FHWA HR Pilot (as reviewed in Section 3-4).

To characterize the full scale and attributes of the HR multimodal transportation network, the report begins by describing and depicting the full scope of the HR and Norfolk roadways, bridges, tunnels, airports, seaports, freight rail and transit network, and pipelines (Section 2).

To guide the process of assessing climate-change *risks* and *consequences* in the region, the report describes the conventional analytical framework for risk assessment that identifies climate stressors (*threats*), the region's *exposure* to stressors, asset *vulnerabilities*, and the attendant property damages and costs (*consequences*) (Section 3). Within this context, the remaining section discusses:

- Information on the HR region's vulnerability to three key *stressors—sea-level rise (SLR), storm surge, and land subsidence*—that shows Norfolk's relatively high level of exposure to climate stressors, putting the city at risk of significant asset loss (Section 3-1);
- Next the section describes the common approaches in USDOT and state/local transportation planning agencies to quantify the costs and risks (safety risks, and traffic disruptions and bottlenecks) through conventional methods such as Benefit-Cost Analysis (BCA) and Lifecycle Cost Analysis (LCCA) used to calculated the costs and benefits of transportation improvement projects (Section 3-2);
- Reviewing the processes implemented by FHWA for incorporating infrastructure and climate risks into the agency transportation asset-management (TAM) practices that in the recent decades have incorporate economic impact analysis (EIA) and conventional input-output (I-O) methodologies—through tools such as RIMS II, IMPLAN, REMI, and computable general equilibrium (CGE)—to compute the direct and indirect costs of disruptive events and their economic impacts (Section 3-3);
- Finally, to put the impact quantification requirements in the context of the existing Federal practices for assessment of climate risks, the study reviews the processes and tools deployed by

agencies such as NASA, USACE and DOT (including the FHWA Gulf-Coast climate change Pilot risk assessment processes) (Section 3-4).

To document the available data that quantify the potential consequences of Norfolk's significant exposure to climate risks, Section 4 provides:

- Recorded damages in Norfolk in the past five decades, as reported in SHELDOUS and NOAA databases (Section 4-1);
- Estimates developed by HR Planning District Commission (HRPDC) on potential range of climate damage in HR and in Norfolk; and by Sandia Laboratories REAcct Tool for estimating the scale of direct and indirect costs of a 4-day SLR related disruption (Section 4-2);
- Studies on the economic impacts of several major industry sectors in HR and Norfolk—the military, aviation, and seaport sectors—and the direct and indirect economic impacts (Section 4-3);
- The imperative of addressing the high indirect consequences of frequent climate-related disruptions (in the context of NOAA's Social Vulnerability Index or SOVi); underscoring the challenges arising from recurrent flooding, business interruption costs, high concentration of uninsured properties, and widespread rates of poverty and job loss in Norfolk.

With respect to adaptation measures for mitigating SLR consequences, the study reviews the conventional processes for assessment of the effective adaptation strategies (Section 5), including the review of the Intergovernmental Panel on Climate Change (IPCC) standards for adaptation measures—*accommodation, engineered protection, and retreat*—as well as the processes that NOAA and the FHWA Gulf Coast Pilot have proposed for SLR adaptation (Section 5-1). The report will also review the type and costs of SLR adaptation projects currently being evaluated in Norfolk (e.g., building floodwalls, tide gates, pump stations, berms and closure walls, and elevation of roads and structures) (Section 5-2).

Section 6 concludes with describing the path forward for completion of Task 1-b and the future Pilot tasks. The section reviews the data and capability gaps identified in the study, and the intent to explore collaboration opportunities with ODU and other members of the Pilot Steering Committee. As this report goes through a comprehensive process of pilot test and evaluation of review by the Department and the HR Pilot participants in the next months, the Volpe team will map out the initial steps for the future tasks. These future steps include a process for linking the risks, vulnerabilities, and adaptation alternatives identified in this preliminary report to implementation of the Volpe Center Lifecycle Infrastructure Resilience Framework –*prevention, protection, threat monitoring, adaptive resource substitution, redundancy, and consequence mitigation*—for addressing climate risks in HR.

Introduction

This report is the deliverable for Task 1a of the Hampton Roads Transportation Climate Impact Quantification Initiative (HR Quantification Initiative). The Task 1a objective is to develop a scoping paper and *preliminary* baseline assessment of the transportation assets in the Hampton Roads Pilot Region. The scope calls for assembling readily-available data on the region's public and private transportation assets—highways, transit stations, rail facilities, seaports, airports, and pipelines—and documenting three dimensions of the HR transportation network: the asset size/magnitude; asset condition; and adaptation actions taken to stem the risks of climate change. Task 1-a conducts the following:

1. **Outlines the study approach, Pilot participants, and data sources.** (Section 1-1);

2. **Describes Hampton Roads' geography, demographics and economy.** (Section 1-2);

3. **Characterizes the size and function of region's transportation assets.** Provides an inventory of the assets, and reviewing each transportation modal asset in terms of function, revenue size/source, scale of operations, and mechanisms for cost analysis and funding improvement projects. (Section 2);

4. **Identify the Region's Climate Stressors and Risk Assessment Methodologies for Addressing them.** Provides a review of the available secondary data on the climate stressors and asset exposure to sea-level rise (SLR)/storm surge/ flooding, an overview of the tools and analytical models and risk assessment processes (Section 3-0); and a preliminary quantification of the regional facilities' vulnerability to damage and loss (Section 4);

5. **Describes current adaptation actions.** Provides a review of the on-going climate adaptation measures implemented or in the planning process, improvements being made, and strategic scenarios developed to adapt to the risks of climate change or prevent future damages (Section 5);

6. **Charts the path forward for conducting a Regional Climate Resilience Assessment.** Building on the information detailed above, this final task identifies the gaps in the available data sources and tools, outlines the approach for the future subtasks, including the development of a *Lifecycle Infrastructure Resilience Framework* for conducting future pilot tasks, and enabling a comprehensive review by the Department and the HR Pilot participants (Section 6).

Following the completion of Task 1a review process, Task 1b will continue (and complete) the efforts outlined under Task 1 of the HR Quantification Initiative. That further work, will constitute the following additional activities/deliverables:

7. **Continued stakeholder outreach.** In consultation with the HR Pilot participants and the public and private actuarial/insurance professionals, the study will incorporate the findings in the preliminary risk and vulnerability estimates.

8. **Comprehensive Baseline Report on HR Region's Transportation Infrastructure Condition and Resilience.** The product will be a new report that will expand upon the information provided in this report (Task 1a scoping paper and preliminary baseline assessment), and will incorporate the preliminary findings of the risk and vulnerability study into the Lifecycle Infrastructure Resilience Framework the Volpe Center has developed for a risk-based approach to transportation system asset management.

1 – Hampton Roads Pilot: Study Approach and Region's Geography

1-1 Study Approach and Pilot Participants

The general approach of this Volpe report is to conduct a high-level overview of the Hampton Roads Pilot region. This report is a work in progress; it is not a planning document; nor is it a risk assessment, economic impact analysis, or a framework for adaptation decision-making. The report, rather, serves as a lens through which the path ahead can be viewed, in the context of the information on the region's asset conditions, infrastructure constraints, and available tools and opportunities for seeking solutions.

The overall thrust of the approach adheres to the conventional steps towards conducting a regional climate risk assessment:

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

Such a process incorporates common strategic planning steps that many agencies involved in technology-deployment are following. An example of this process is the NASA 8-step adaptation framework that the agency's Climate Adaptation Science Investigator (CASI) Working Group is implementing. CASI is further described in Section 3-4 for its application to the Hampton Roads Pilot.[1] The same framework also incorporates the FHWA 11-Step Climate Change Template for conducting transportation facility condition assessment and adaptation strategies, developed in Phase 2 of the Gulf Coast Pilot Study (Gulf Coast 2) (as described in Sections 3-4 and 5-1).[2]

This report follows the general structure of the 11 step Gulf-Coast 2 Template for first identifying the elements of climate risks and vulnerabilities in the region, followed by an examination of the potential adaptation strategies to be implemented. The first steps of the Template are as below:

- Steps 1 through 3: describe the HR transportation network's geographic context, facility attributes, infrastructure exposures and potential climate stressors (Sections 1 and 2);
- Step 4: describe the existing climate models and scenarios and the HR transportation asset conditions that constitute the foundation for strategic actions (Section 3) ;
- Step 5: describe the performance gaps of the existing network facilities and the findings of the economic models used to quantify the existing and potential impacts and costs (Section 4);
- Step 6: describe the range of adaptation options that are currently implemented or being evaluated (Section 5).

Steps 7 through 11 of the Gulf Coast 2 Template—not included in the scope of this report—address the performance of each adaptation measure and conduct an analysis of the benefits, cost, and economic impacts of the proposed projects. Once again the scope of the current Volpe Center project does not include conducting risk analysis, benefit-cost or economic impact analysis; nor does it conduct adaptation investments analysis. However, based on the secondary data available from the Pilot participants, future Volpe Center task reports and subsequent phases of the HR Pilot will address these decision elements.

[1] *Climate Risk Management Plan: Managing Climate Risks and Adaptation to a Changing Climate*. NASA, 2014.
[2] *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Course Study, Phase 2; Task 3.2: Engineering Assessments of Climate Change Impacts and Adaptation Measures*. FHWA, Aug. 2014.

Pilot Participants and Steering Committee

The Hampton Roads Steering Committee (Figure 1) consists of the Intergovernmental Pilot Project (IPP) working groups, Federal Liaisons, Old Dominion University (ODU), and HR planning agencies—Hampton Roads Planning District Commission (HRPDC), HR Transportation Planning Organization (HRTPO), and municipal and state government entities—described as a "whole of government" entity by the IPP officials. These players have to a large extent adopted the principles of the climate-change adaptation framework described above. The structure of the HR Pilot is outlined below, highlighting the two groups that DOT supports, the Infrastructure Working Group and Economic Impact Advisory Committee.

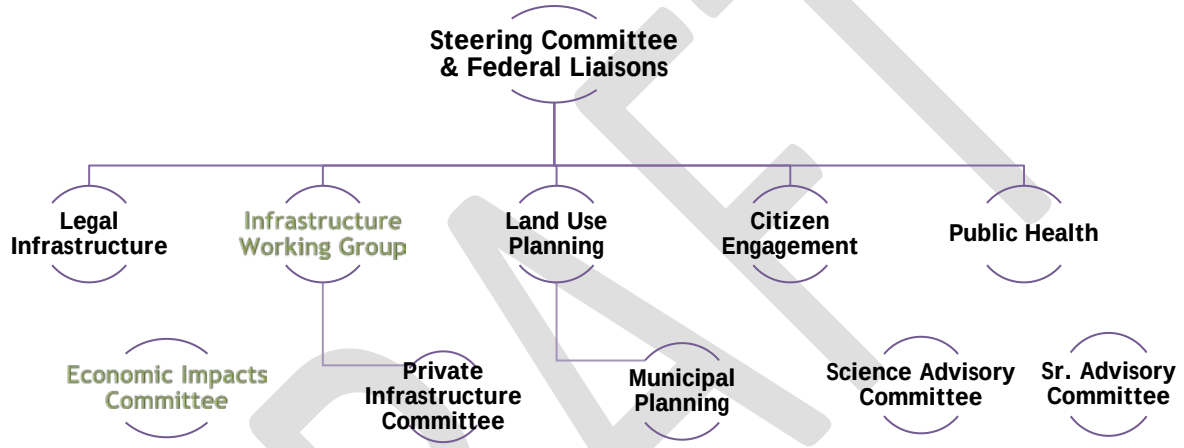


Figure 1. Hampton Roads Pilot Structure.[3]

Data Sources

Task-1a of this study has relied on 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. This includes economic impact assessment tools and methodologies available for quantification of the economic costs of climate change. These tools and their associated data sources—as described in Sections 3-3 and 3-4—will be further described and used in future phases of the HR Pilot. For this report, the primary sources of data have included: FEMA HAZUS-MH, SHELDUS, NOAA and National Climate Data Center (NCDC) databases accessed through GIS portals, and reports prepared by

[3] 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. Army Corps of Engineers. For more information on the Pilot, including its charter and comprehensive Phase I report of 2015, see: http://www.centerforsealevelrise.org/research-resources/pilot-project-resources

the Virginia Institute of Marine Science (VIMS), Virginia DOT (VDOT), USDOT, Old Dominion University (ODU), Hampton Roads Planning District Commission (HRPDC), and the HR Transportation Planning Organization (HRTPO). Many other public and academic studies and data sources have also been consulted. Appendices B and C provide the study References and an inventory of Data Sources consulted for this report.

1-2 Hampton Roads: The Region's Geography, Economy, and Demographics

This section provides an overview of the HR region by describing the geography, demographics, and economic sectors of Hampton Roads (HR).

Geography of Hampton Roads and the Pilot Region

The HR[4] region is spread over 16 jurisdictions, including 10 cities and 6 counties. It is part of the 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.[5] The cities are: Chesapeake, Franklin, Hampton, Newport News, Norfolk, Poquoson, Portsmouth, Suffolk, Virginia Beach, and Williamsburg. The six counties in HR are: Gloucester County; Isle of Wight County[6]; 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 17-jurisdiction HR.

Two of the HR cities—Norfolk and Virginia Beach— are relatively larger cities (each with populations of over 245,000 and 450,000, respectively)[7], and the other eight are smaller. The HR Pilot has designated the City of Norfolk, the City of Virginia Beach, and Joint Expeditionary Base Little Creek/Fort Story and the surrounding neighborhoods and watersheds of Pretty Lake, Lake Whitehurst, Little Creek and Little Creek Amphibious Base within the cities, as the initial focus area of the Pilot. Given the absence of detailed network operational and economic data at the lower level of aggregation (as in the case of Pretty Lake), the study will have a two-faceted focus: one on Norfolk/Pretty Lake (depending on the context and availability of disaggregated data), and the second on the HR region as a whole. Within this dual perspective,

[4] 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.
[5] "Metropolitan and Micropolitan Statistical Areas." See: http://www.census.gov/population/metro.
[6] Includes the Town of Smithfield.
[7] Ibid.

relevant data are analyzed either for the City of Norfolk/Pretty Lake geographic area to describe in detail the identified climate risk and vulnerabilities, or for the HR region in general, with cross matrices that create comparisons and contrasts between the inter-related geographic aggregations. Figure 2 depicts the HR region as a whole, with the areas of Norfolk and Pretty Lake (Norfolk and Virginia Beach) highlighted within.

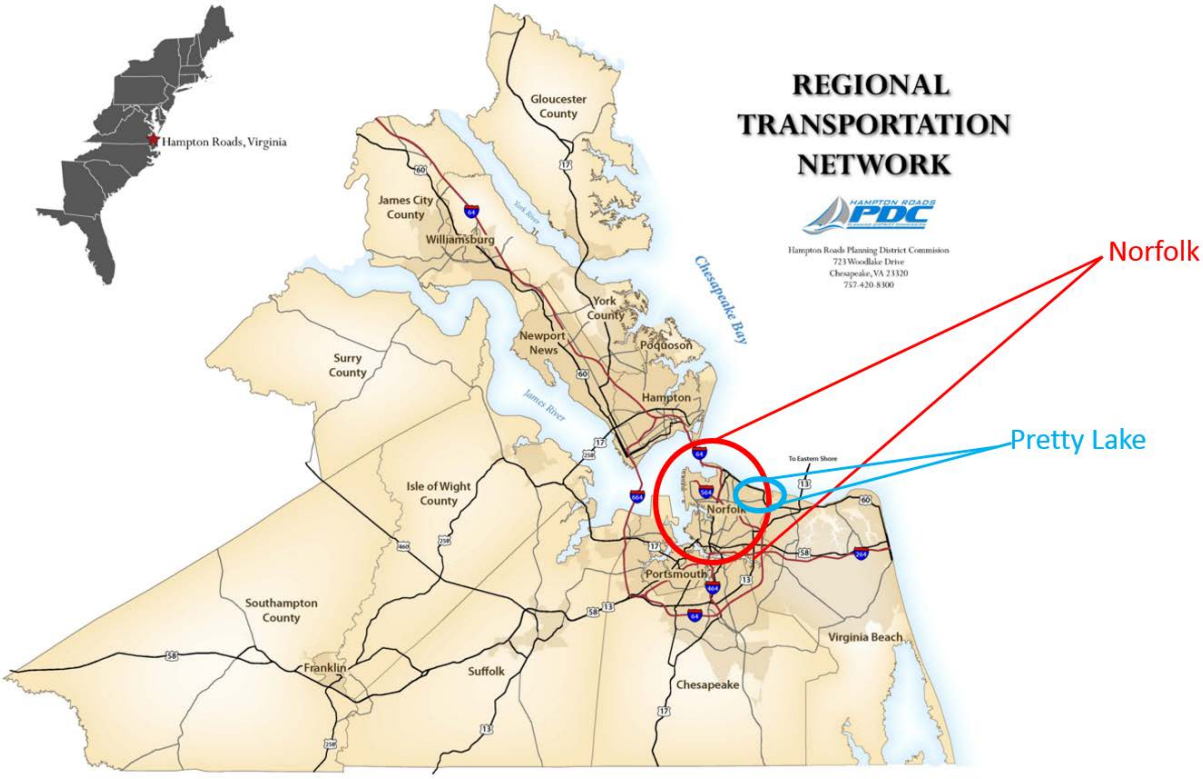


Figure 2. Hampton Roads, Norfolk, and Pretty Lake. (Source: HRPDC)

Incomes, Jobs and Employment Sectors

The HR region's total employment in 2013 was 720,000. Norfolk's employment of 136,300 comprises 19% of the region's total employment (compared to its population share of 14.6%). HR has had a lower rate of employment growth compared to the rest of Virginia (at near zero growth rate compared to 1.72% growth in Northern Virginia and 0.99% statewide), which has in part been attributed to its lower business startup rate.[8] This also corresponds to a regional slow-down in population growth, which is in large part due to the loss of population in Norfolk.[9]

[8] *HR Vision – Annual Report*. HR Partnership, Sep. 2013. The report 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

The region is home to 16 federal agencies, including numerous Department of Defense installations and the world's largest naval station, Naval Station Norfolk. 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%; and the worst-performing sector the Information Sector at a rate of -30.13%. Figure 3 shows the Norfolk share of HR employment by industry (comprising mostly around 10-15% of the employment in each sector). The Figure highlights the significant share of military employment in Norfolk (largely attributed to Naval Station Norfolk), accounting for close to a third of the employment.

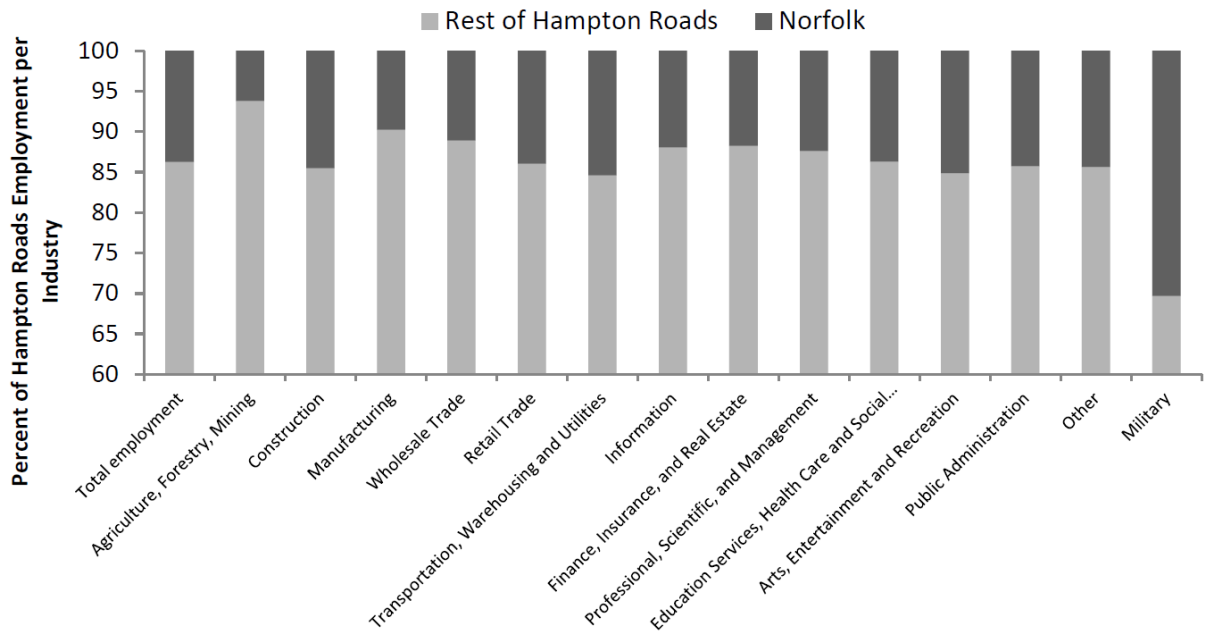


Figure 3. Norfolk share of total HR employment by industry. (Source: Sandia National Lab, U.S. Census Bureau)

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 in Section 4-3.

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). See: http://visionHamptonRoads.com

[9] 2035 *VA Surface Transportation Plan, Ch. 2: Changes in Pop., Employment and Travel in VA*. 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.

Income Levels and Growth

According to the 2015 *State of the Commonwealth Report*[10] the median household income in 2013 in Norfolk was $44,747, compared to $62,666 for the state as a whole.[11] Table 1 compares median and real income levels (adjusted for cost-of-living) in Norfolk, the Commonwealth of Virginia, and the United States in 2013.

Table 1. Income and cost of living in Norfolk, Commonwealth of Virginia, and the U.S. (Source: Old Dominion University)

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
Commonwealth of Virginia	$62,666	3,055,863	103.2	$61,925
United States	$53,047	116,291,033	100	$53,047

The Norfolk/Virginia-Beach MSA had a lower rate of income growth compared to the Washington DC-Arlington-Alexandria-Maryland MSA (a small rate of growth at 0.18%) in the 2009-2013 period, then declining slightly in 2014 (to -0.10%).[12] 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 the Virginia Beach–Norfolk–Newport News Metropolitan Statistical Area (MSA). However most of the income statistics reported in the study are for the City of Norfolk.

DRAFT

[10] *2015 State of the Commonwealth Report*. ODU, Strome College of Business, December 2015.

[11] 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.

[12] 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.

2 – Hampton Roads: The Multimodal Transportation Network

This section provides an overview of the HR transportation network, with specific focus on Norfolk, depending on data availability. Figure 4 depicts the regional commuting patterns to and from Norfolk, based on data from the U.S. Census Bureau *American Community Survey*.[13]

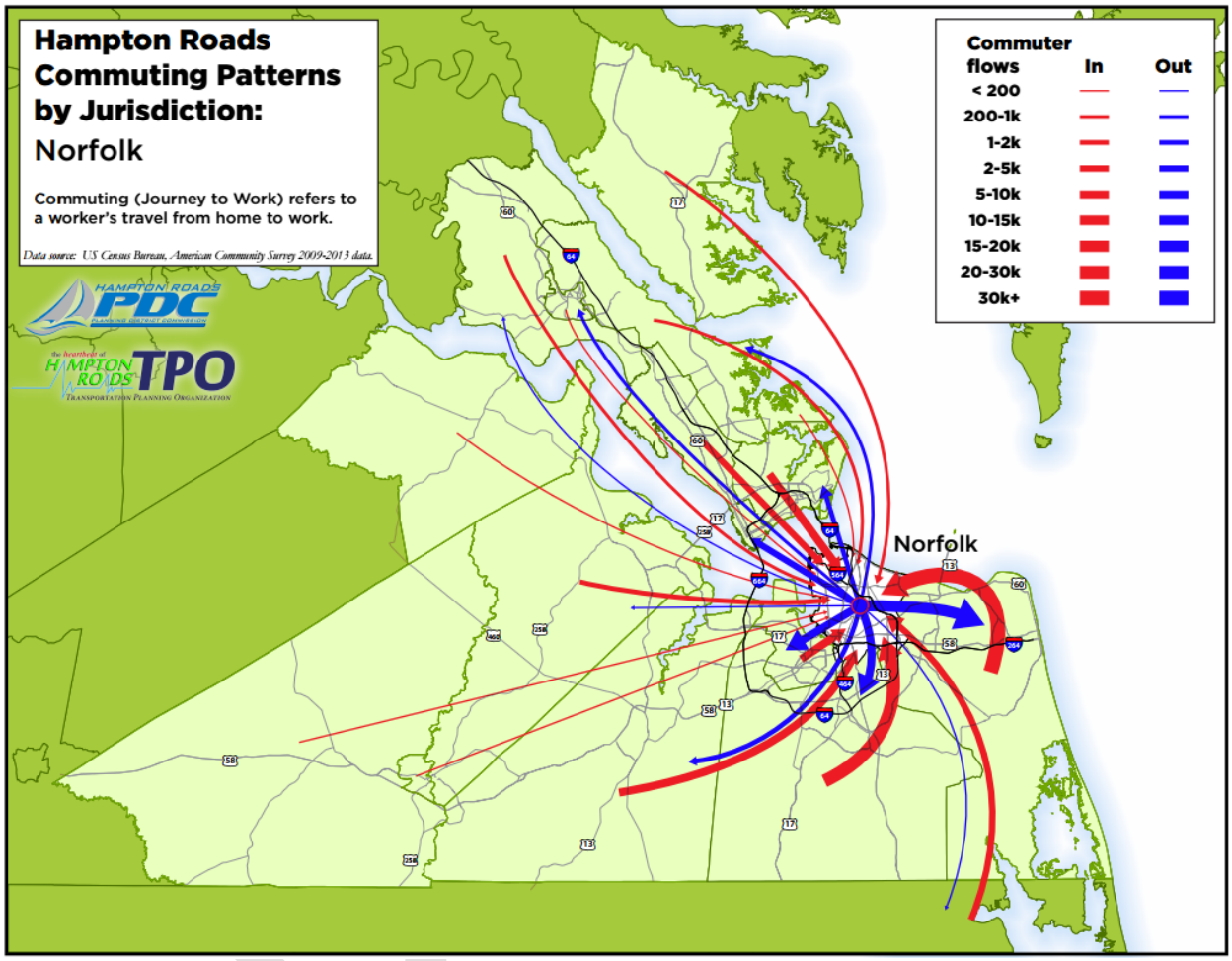


Figure 4. Norfolk commuting flows in and out of the city. (Source: Hampton Roads Planning District Commission)

Further highlighting the Norfolk and Pretty Lake focus areas is Figure 5 below, showing Norfolk/Pretty Lake highways, bridges, ports, and rail lines.

[13] "American Community Survey (ACS)". U.S. Census Bureau. See: https://www.census.gov/programs-surveys/acs

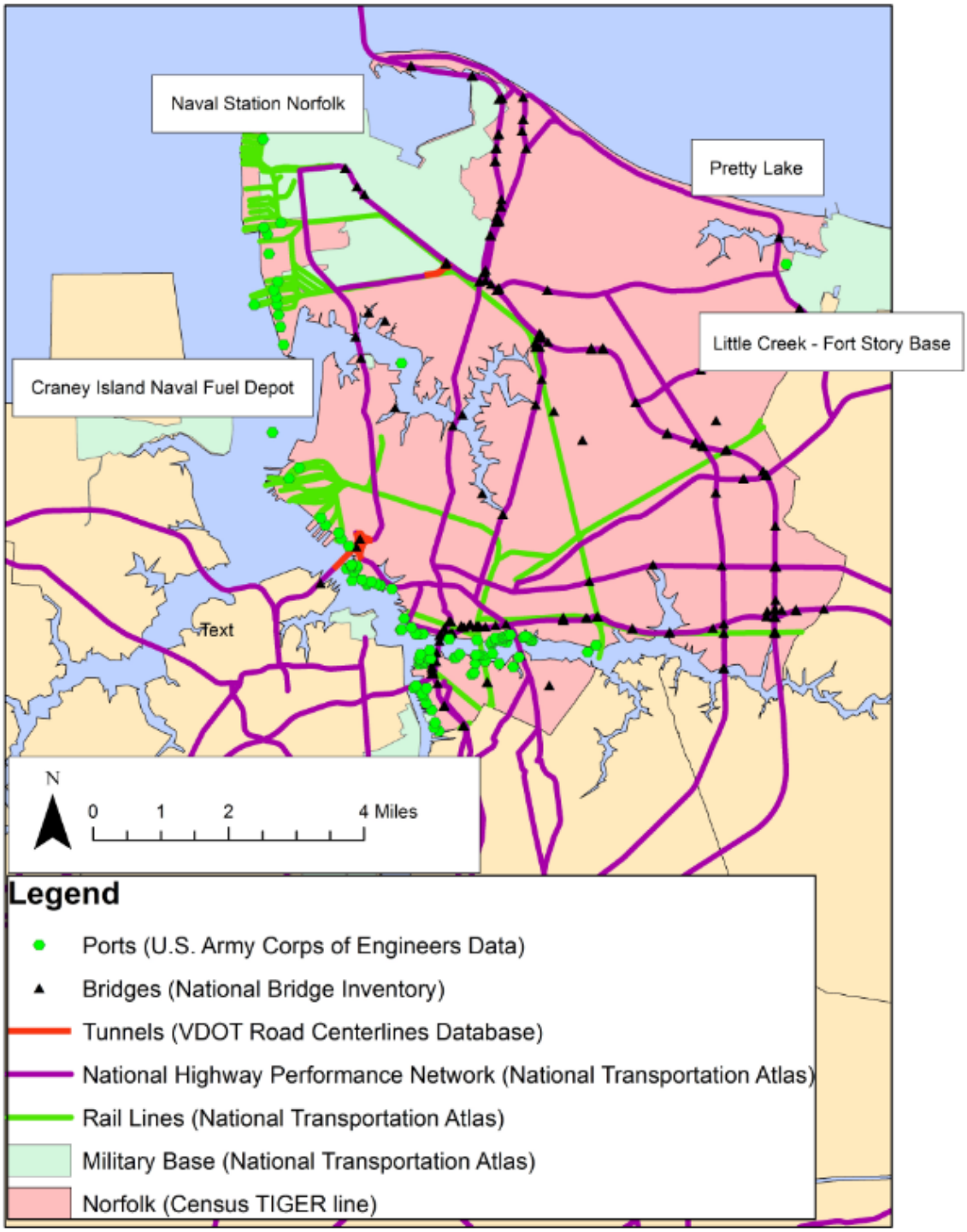


Figure 5. Norfolk/Pretty Lake highways, bridges, ports, and rail lines. (Source: National Transportation Atlas Database (NTAD))

Roads

Table 2 shows the distribution of the highway network components for HR and Norfolk (by road mileage). The data are from the VDOT road centerline database as described by the HRPDC

Phase III report, and the Norfolk Open GIS website. Daily vehicle miles traveled (DVMT) in HR is estimated at about 42.2M, or 19% of the state DVMT, commensurate with the City's share of population.[14] Table 3 shows the total mileage and valuation of Norfolk highways, for each road category in Norfolk and HR.

Table 2. Roadway centerline miles in Hampton Roads. (Sources: HRPDC Phase III Report; Norfolk OpenGIS)

Infrastructure/Roads	HR Total (Centerline Miles)	Norfolk Total (Centerline Miles)
Interstate	250	102
Primary	1,460	98
Secondary	2,216	169
Local or Private	7,841	643
Base Roads (Military)	NA	82
Total Road-miles	**11,767**	**1,094**

Table 3. Total valuation of Norfolk highways, by category. (Source: Hazus-MH)

Category	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
Grand Total	**172.4**	**520.3**	**$1,407,784**

Bridges

Water divides Hampton Roads into many sub-regions, making bridges a prominent feature of the HR landscape, numbering 1,223[15] of all length, function, and condition. Indeed, HR has more lane-miles of bridges than *all* other metropolitan areas in Virginia, and many others nationally.[16] HR is often described by its leaders as "the most infrastructure dependent-place on the East Coast".[17] In Norfolk, there are 190 bridges reported in the 2011 version of the

[14] *Climate Change in Hampton Roads, Phase III: Sea-Level Rise in Hampton Roads, VA*. HRPDC, July 2012.
[15] *HR Regional Bridge Study*. HRTPO, Nov. 2012.
[16] *"2034 Long-Range Transportation Plan"*. HRTPO, Jan. 2012.
[17] 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.

National Bridge Inventory, including 173 highway bridges, 12 non-highway road bridges and 5 rail bridges.[18] Of these, there are three major bridge-tunnel combinations that have major economic value to the region (to be discussed in the following section on tunnels, which are another critical part of the HR transportation network). Figure 6 above depicts the prominent presence of bridges in Norfolk. The 2012 HRTPO *Regional Bridge Study* describes the prominent part 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.[19] Table 4 describes the attributes of the 190 bridges in Norfolk. Figure 6 depicts the prominent presence of bridges in Norfolk.

Table 4. Attributes of Norfolk Bridges (Source: HAZUS-MH)

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	322
Principal Arterial - Other Freeways or Expressways	2	202	27,090	42,500	5
Other Principal Arterial	32	5,073	935,164	1,570,500	264
Minor Arterial	12	2,203	155,348	244,500	157
Collector	6	364	58,390	72,500	29
Local	3	48	7,276	9,425	50
Grand Total	**190**	**25,272**	**7,722,255**	**18,798,088**	**827**

[18] The HAZUS database includes only 173 highway bridges and 5 rail bridges for Norfolk.

[19] HRTPO *HR Regional Bridge Study:* 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.

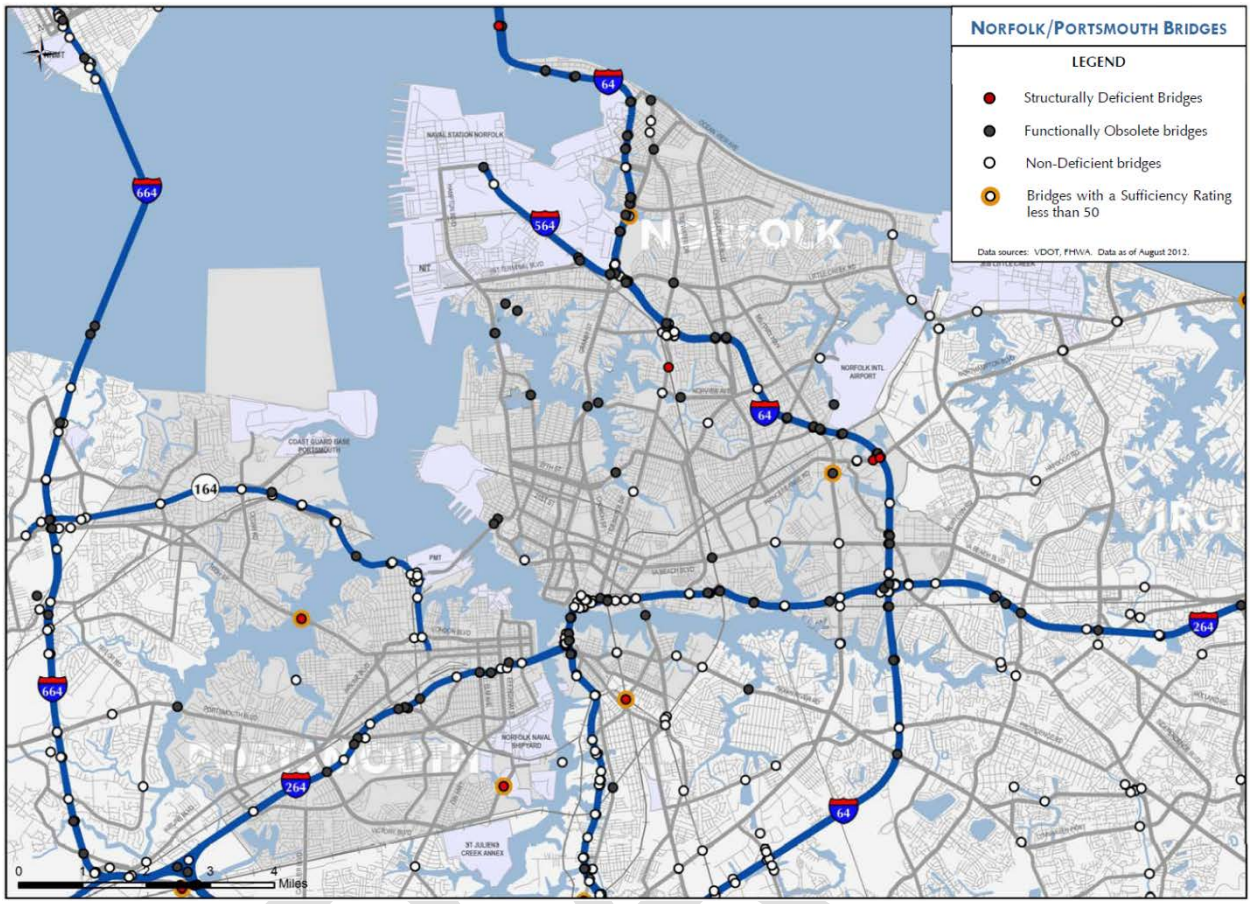


Figure 6. Norfolk roads and bridges. (Source: HRTPO)

Bridges in HR are aging, as are many other bridges in the nation that were built over 60 years ago. The average bridge age in HR is 37 years, slightly lower than comparable metro areas. Bridge condition in HR, in parallel with the structures' age, is also deteriorating. As bridges age, they are more susceptible to structural or functional deficiencies. Standard engineering criteria for bridge "deficiency" consist of ratings for "structural deficiency" and "functional obsolescence." For bridges built overwater that have underwater substructures, the "Scour Index" is one key factor for the standard condition rating. Two additional sources of data provide other indicators of bridge condition in HR. The National Bridge Inventory data in the National Transportation Atlas Database show that 3 of 190 Norfolk bridges (1.6%) are structurally deficient; and 68 of 190 of Norfolk bridges (35.8%) are functionally obsolete.

Another source of data is the HRTPO Bridge Study, which reports a total of 77 bridges in HR (6.3%) are classified as structurally deficient and another 379 bridges are "functionally obsolete." Adding up the two classifications, a total of 456 bridges in HR (37%) are classified as

"deficient," making HR the 2nd highest nationwide in its size class in this category.[20] Appendix C describes the standards for bridge condition classification. Table 5 compares the HR bridge condition rating with the results of a November 2015 GAO report stating that nearly a quarter of the Nation's bridges are "deficient" (10% "structurally deficient"; and 14% "functionally obsolete"). The table underscores the fact that while 37% of HR's 1,223 bridges are classified as "deficient", only 6.3% (77 bridges in HR) are classified as "structurally deficient", a potential safety risk. This represents a significant distinction from "functionally obsolete," a classification that designates no safety risk. Comparing the nation's ratio of 10% with the 6.3% rate of "structurally deficient" bridges in HR shows that condition of bridges in HR does not indicate above-average safety risks. However the large percentage of functionally obsolete bridges (31%) may possibly be indicative of the bridge-intensive geographic location of HR.

Table 5. Highway bridge condition ratings in HR. (Sources: Source: GAO; HRPDO Bridge Report)

Condition Category	Count of HR Bridges	% of HR Bridges	% of Bridges Nationally
Functionally Obsolete (no safety risk)	379	31%	14%
Structurally Deficient (potential safety risks)	77	6.3%	10%
Total Functional and Structural Deficiency	456	37%	24%

The HAZUS-MH bridge deficiency data are based on their score on the Scour Scale that assigns values ranging from 0 to 9, where 0 is the greatest vulnerability (indicating "bridge is closed); a score of 9 indicates that the bridge is not over water; and a score of 8 indicating the lowest level of vulnerability. According to the HAZUS-MH manual, only bridges with a score lower than 3 have a significant probability of failure due to flooding. Appendix C describes the scoring and rating system used in bridge condition ranking.

Table 6 shows the scour indices for the 173 bridges for Norfolk highway bridges. The scores are relatively high, suggesting that bridges in Norfolk are in acceptable condition, with only 1 bridge scoring 0 (indicating the bridge is closed), with none scoring below 3; the lowest score of 5 assigned to 117 bridges (65% of all bridges); and a score of 8 assigned to the remaining 32%. The total valuation of $628.5M for the 173 highway bridges in Table 6 suggests an average cost of $3.6M to rebuild each highway bridge. Many DOT experts have commented on the low valuation of the regional bridge assets in the HAZUS-MH database. This report recognizes this downward bias. However, as noted earlier, the purpose of this study is not to conduct project-planning but rather provide a high-level scan of the available information.

[20] 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.

Table 6. Highway bridges in Norfolk. (Sources: HAZUS-MH; 2001 National Bridge Inventory)

Decade Built	Number of Bridges	Total Valuation	Worst Scour Index Reported for Any Bridge in the Age Group (8 is the best possible score, i.e. lowest vulnerability)
1920s	1	$1,908,000	8
1930s	1	$3,571,000	8
1940s	2	$4,387,000	8
1950s	6	$20,798,000	5
1960s	51	$153,971,000	8
1970s	44	$207,061,000	5
1980s	26	$92,794,000	5
1990s	41	$136,411,000	5
2000s	1	$7,592,000	0
Grand Total	**173**	**$628,493,000**	

Valuation of rail bridges in HR, as documented in HAZUS-MH is even lower than what the experts view as reasonable. Table 7 shows the HAZUS 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 7. Railway Bridges in Norfolk. (Sources: HAZUS-MH; 2001 National Bridge Inventory)

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**

Low as the HAZUS-MH valuation of the 173 Norfolk bridges is, the fact remains that bridges are particularly costly to build and maintain. VDOT has estimated the costs of constructing bridges to be 4 to 6 times higher than typical urban roadway reconstruction costs. This has contributed

to funding not keeping up with bridge maintenance needs.[21] Bridge length is a key factor in the engineering complexity and rebuilding costs. The 1,223 bridges in HR are particularly substantial in length: in total they span 565,000 feet, or an average of 460 feet for each bridge.[22] Given the higher costs of bridge maintenance costs compared to typical roadway maintenance costs, the assessment of the condition of HR bridges as part of the region's climate change adaptation planning process plays a prominent role, as discussed in Section 5.

DRAFT

[21] *Climate Change Adaptation Case Studies, Hampton Roads, VDOT.* FHWA, 2011. Also, in a 2009 report, FHWA referred to escalating costs of bridge maintenance, pointing out that some additional $71B was need to address the national backlog of nearly 150,000 deficient bridges in the country.

[22] Placed end-to-end, they span over 107 miles in total. The total deck area of HR bridges is 28,227,000 sq. ft. This ranks HR 8th highest among 35 comparable metropolitan areas (after New Orleans, St. Louis, Kansas City, Austin, San Antonio, Baltimore, and Pittsburgh).

Tunnels

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

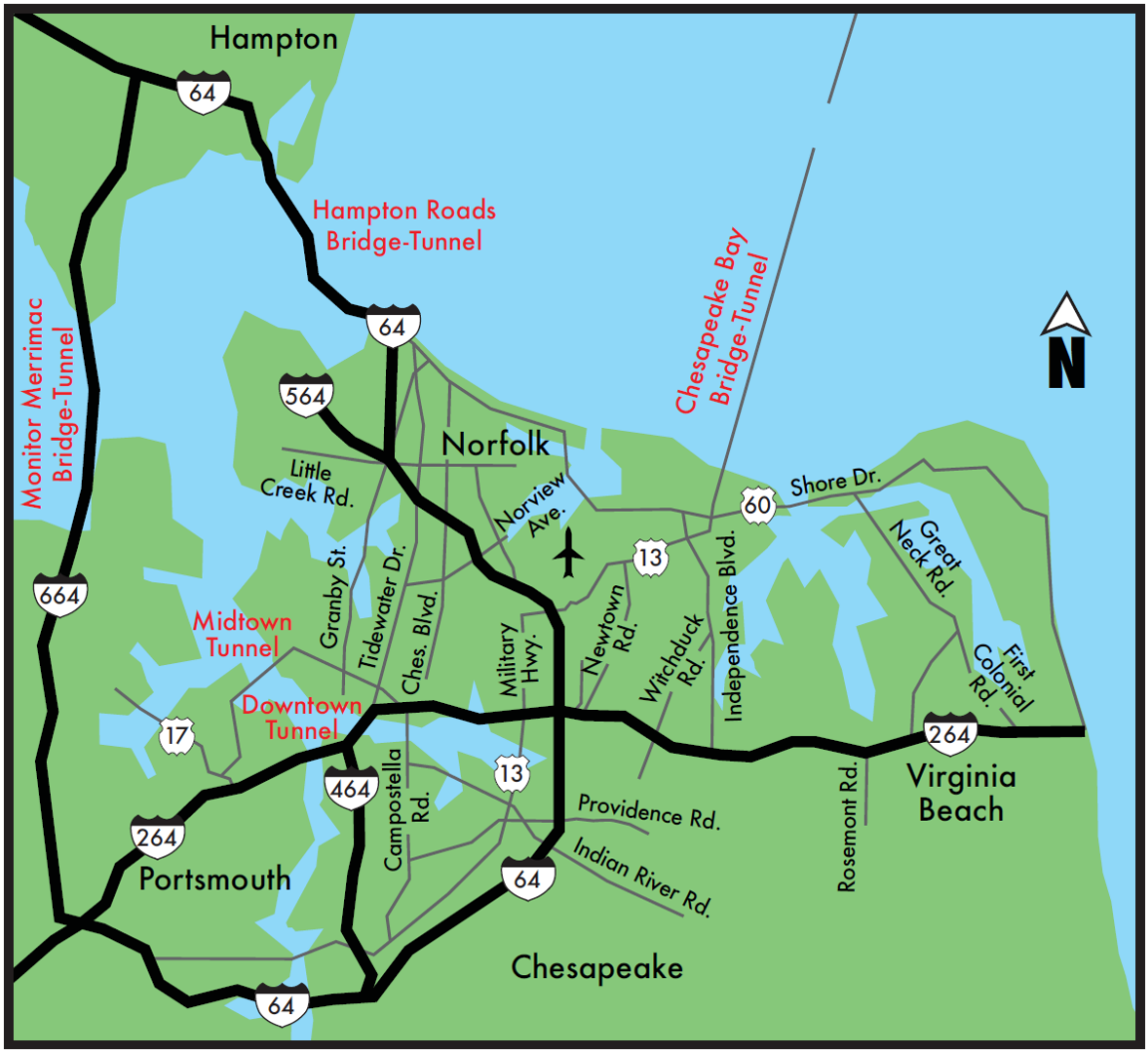


Figure 7. Tunnels connecting Hampton Roads. (Source: Old Dominion University)

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.
Water Crossing:	Spans Hampton Roads Harbor.
Connects:	Connects Hampton and Newport News to Norfolk and Virginia Beach.
Length:	3.5-miles
Traffic Volume:	Nearly 3,000,000 vehicles per month, and over 100,000 vehicles per day during

	the tourist season. During heavy traffic, many motorists use the MMMBT on I-664 instead.

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.
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 (e.g., 50,000 vehicles per day during peak tourist season).

Downtown Tunnel (I-264)	
Opened:	The first two-lane Downtown Tunnel opened in 1952; the second opened in 1987.
Water Crossing:	Spans the Elizabeth River.
Connects:	Links Norfolk and Portsmouth.
Length:	0.65-miles
Traffic Volume:	The Downtown Tunnel carries over 3,000,000 vehicles per month.

Midtown Tunnel (Route 58)	
Opened:	The Midtown Tunnel opened in 1962 as the second tunnel connecting Norfolk and Portsmouth (built after the Downtown Tunnel).
Water Crossing:	Spans the Elizabeth River.
Connects:	Links Norfolk and Portsmouth.
Length:	0.8-miles
Traffic Volume:	The Midtown Tunnel carries over 1,000,000 vehicles per month.

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.
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:	Average daily traffic in the summer months is about 13,000 to 14,000/day, about twice the daily rate in winter.

Unlike bridges, which have been overseen by the National Bridge Inspection Program (NBIP) for over 30 years, tunnels have not been subject to national inspection requirements or standards. In 2012 MAP-21 directed 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.[23] 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.

Figure 8. Chesapeake Bay Bridge-Tunnel. (Source: cbbt.com)

Hampton Roads tunnels are regularly inspected, and benefit from a VDOT continual maintenance and operations program. 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.

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 structurally deficient and functionally obsolete. The sufficiency ratings[24] of the bi-directional bridge portions of these complexes range from 83 – 95.3 for the MMMBT, and 63.9 – 82.7 for the HRBT. The CBBT, which is privately operated, is classified in-whole as non-deficient.[25]

With respect to tunnel capacity and congestion, four of the five major tunnel complexes in Hampton Roads are considered "choke points" and bottlenecks (Figure 9). To address these

[23] *Press Release: Federal Highway Administration Launches New National Tunnel Inspection Program*. FHWA, July 14, 2015. See: https://www.fhwa.dot.gov/pressroom/fhwa1553.cfm

[24] Sufficiency ratings are numerical ratings for each bridge based on its structural evaluation, design and function, and public importance. These components are used to obtain a numeric value between 0% and 100%, with a sufficiency rating of 100% representing an entirely sufficient bridge.

[25] *HR Regional Bridge Study*. HRTPO, Nov. 2012.

capacity constraint, VDOT, since the 1990s, has 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* (2000), 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.[26]

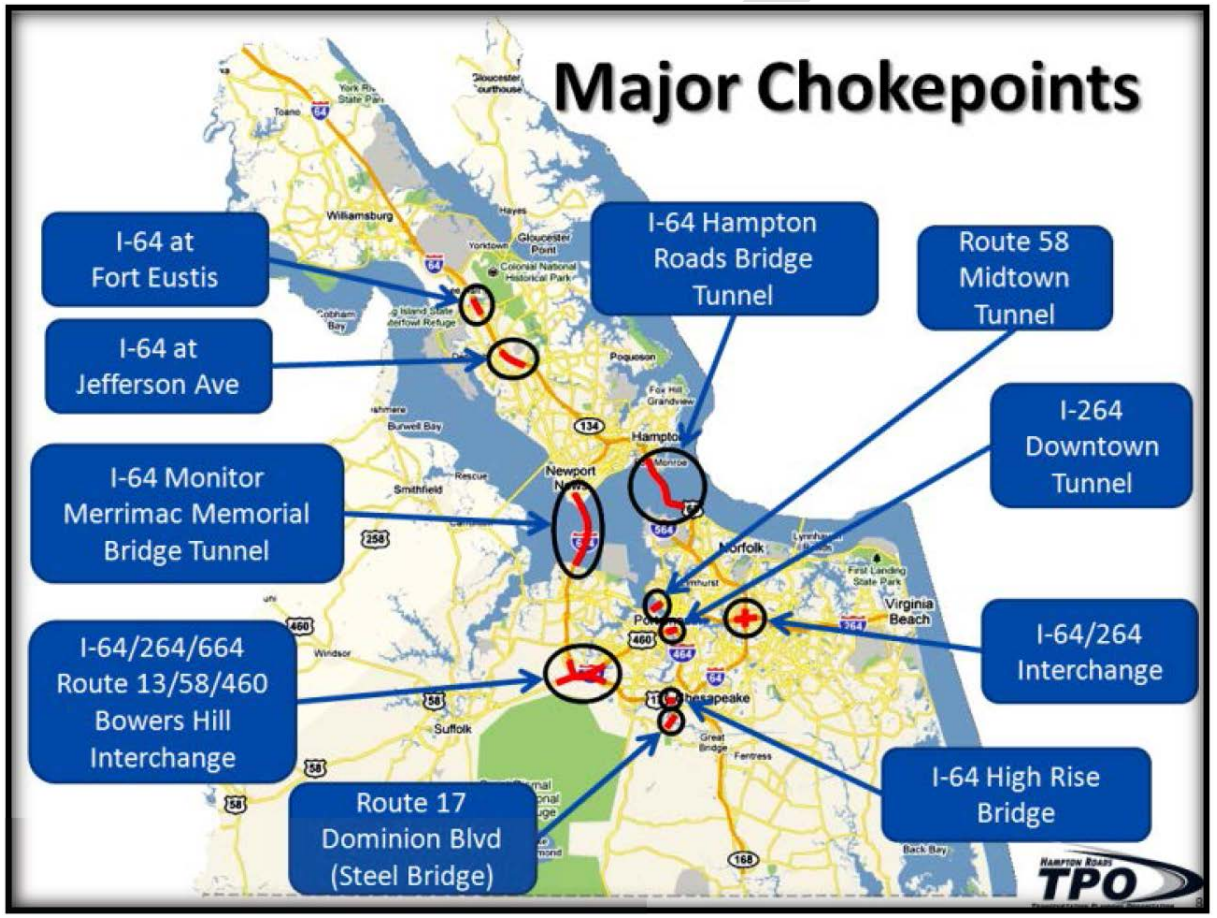


Figure 9. Major traffic chokepoints in Hampton Roads. (Source: HRTPO)

Railroads

According to the 2015 Railway Network from the National Transportation Atlas, there are 65.2 miles of rail corridor in Norfolk, and a total of 85 miles of track. Table 8 shows the total length of the railway network. The Tide is a light-rail service with 7.4-miles of track in downtown

[26] "Hampton Roads Crossing Study". VDOT. See: http://hamptonroadscrossingstudy.org

Norfolk, as described in the Transit Section. Figure 10 maps the extent of the greater Hampton Roads rail network, as well as closer detail of rail lines in and around Norfolk.

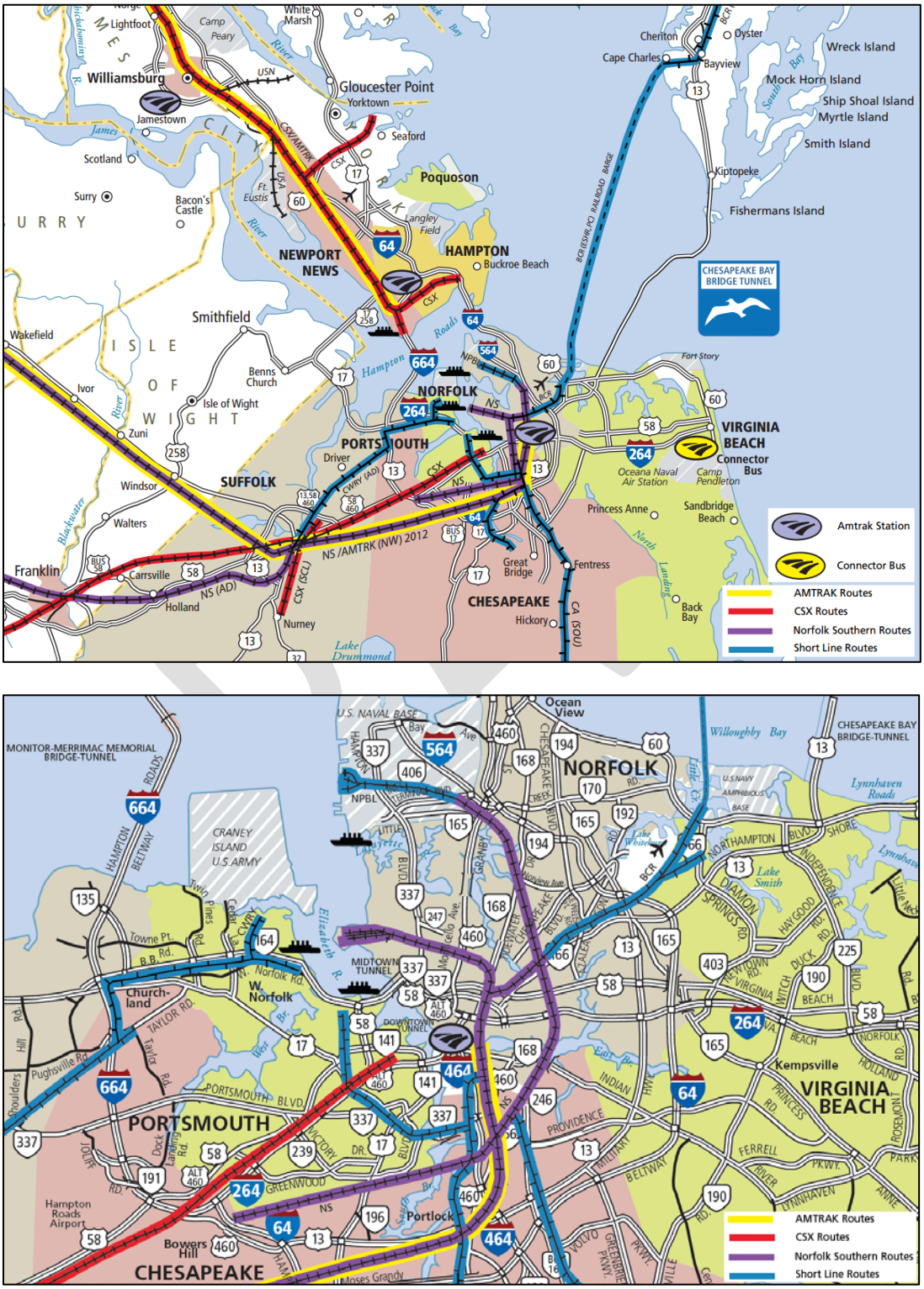


Figure 10. Hampton Roads rail lines; Southside Hampton Roads rail lines (Norfolk & vicinity). (Source: VA DRPT)

Table 8: Railway network in Norfolk. (Sources: NTAD and Norfolk OpenGIS)

Rail Network	Miles of Rail Corridor	Miles of Tracks
Passenger Rail (Amtrak)	1.0	2.0
Passenger Commuter Rail	7.4	14.8*
Freight Rail	56.8	68.2**

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

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). 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.[27] Appendix C shows the HAZUS cost estimates for specific components of the rail network.

Freight Network: Trucking and Multi-modal Operations

HRTPO conducted a study in 2012 on the HR regional freight.[28] 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 9 summarizes the four freight transfer facilities in Norfolk. This report's Seaports' section provides some data on freight container movement in Port of Virginia.

Table 9. Freight facilities in Norfolk (Source: 2015 National Transportation Atlas)

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

[27] 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 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.

[28] *Hampton Roads Regional Freight Study, 2012 Update*. HRTPO, Sept. 2012.

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.[29] 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 11).
- Operates 9 light rail transit vehicles
- Averages over 1.65M passenger trips per year.[30]
- The majority of the line is ¼ mile or less from the waterfront; several stations lie within 800' from the water, including one less than 1/10mi from the coastline. The light rail track itself lies less than 20' from the water in multiple locations.[31]
- HRT is examining alternatives analyses for potential extension of The Tide to Norfolk Naval Base, Old Dominion University, Norfolk International Airport, and Virginia Beach.

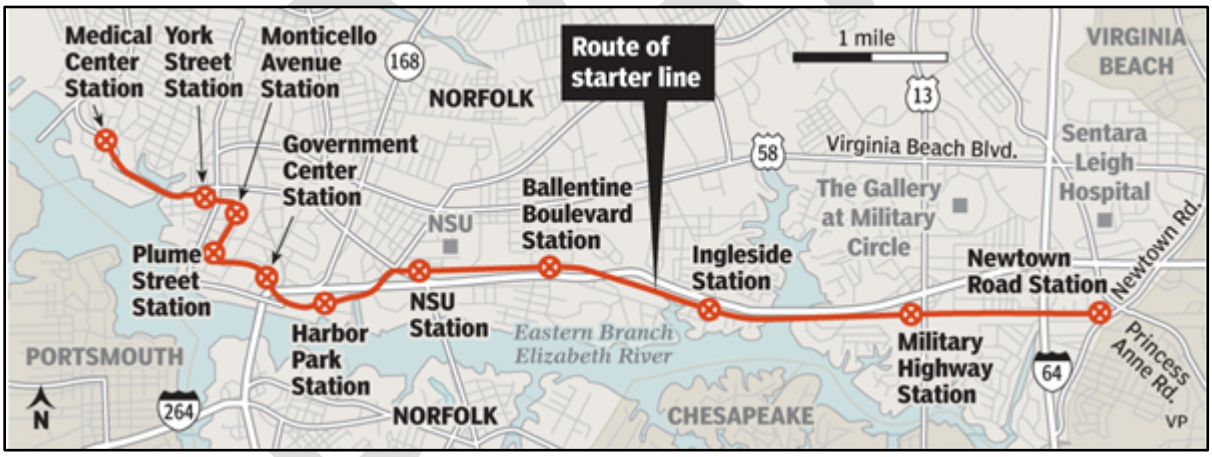


Figure 11. The Tide light rail system. (Source: www.hamptonroads.com)

Bus Services

- Provided over 17.9 million passenger trips in FY14 to people in Chesapeake, Hampton, Norfolk, Newport News, Portsmouth and Virginia Beach.[32]

[29] "Hampton Roads Transit Services". HRT. See: http://gohrt.com/services
[30] *Ridership Report for April 2014.* HRT, April 2014.
[31] Analysis based on Google Earth imaging.
[32] HRT, *Ridership Report for April 2014.*

- Fleet includes 302 buses (255 diesel buses, 37 hybrid buses and 10 trolley-style buses).[33]
- 3,500 bus stops & 199 bus stop shelters.
- Includes six major transfer centers – four of which are within a ½ mile of the coast (e.g., Newport News Transfer Center is only 195' from the waterfront).[34]

Ferry Services

- Ridership typically averages ~350,000 ferry passenger trips per year.[35]
- Operates routes between Norfolk and Portsmouth on the Elizabeth River (Figure 12).
- Includes four ferry docks.
- Fleet includes three 150-passenger ferry vessels.
- Waterfront parking facility (Portsmouth).

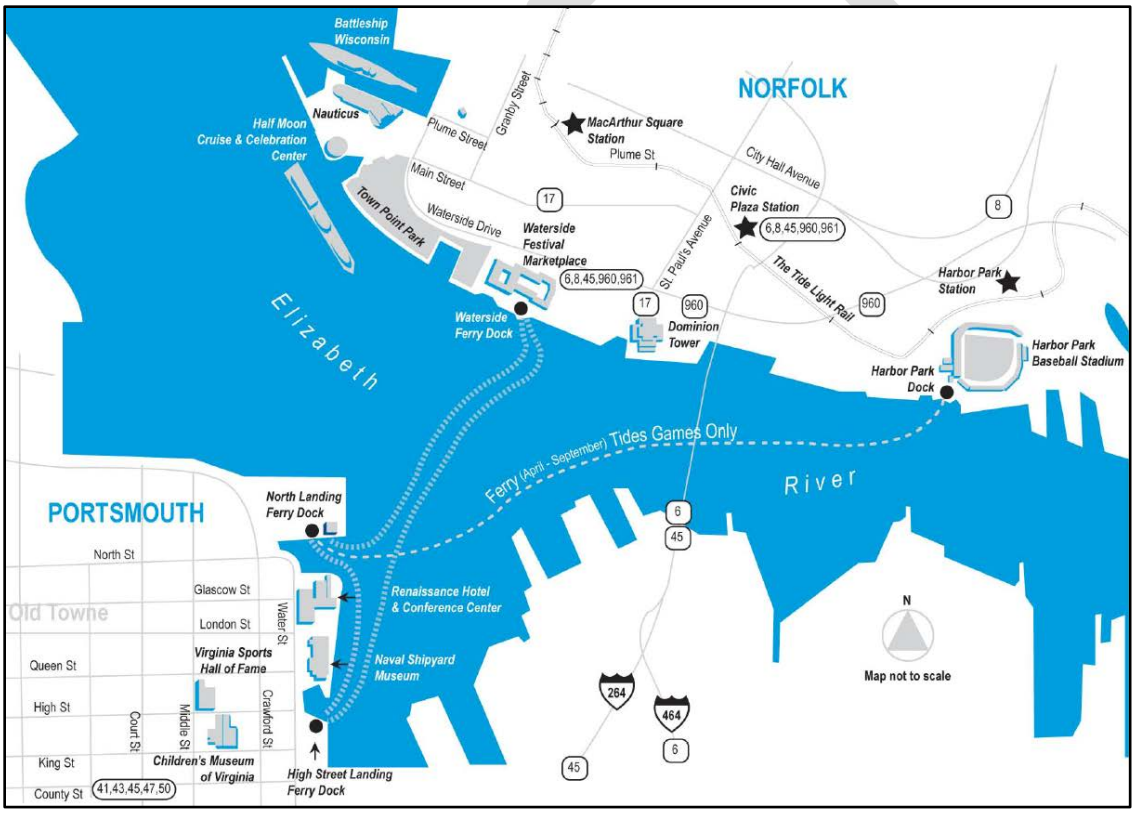


Figure 12. Hampton Roads Ferry Routes & Docks (Source: Hampton Roads Transit)

[33] As of August 2011.
[34] Analysis based on Google Earth imaging.
[35] HRT, *Ridership Report for April 2014.*

Airports

The Commonwealth of Virginia has a total of nine primary commercial airports, with total enplanements of 24,480,117 in 2013.[36] For 2014, the FAA National Plan of Integrated Airport Systems (NPIAS) database indicates total enplanements of 24,467,633.[37] Table 10 shows airport traffic at Virginia's top four airports that, with total enplanements of 23.6M, account for over 96% of total aviation traffic within the Commonwealth.

Table 10. Enplanements at Virginia's four busiest airports. (Source: *2015 State of the Commonwealth Report*)

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

Norfolk International Airport (ORF), an FAA NPIAS classified small/non-hub airport with a significant military usage, is located in a densely populated area adjacent to the Chesapeake Bay.[38] 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.[39]

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 11 shows Total Operations for ORF, IAS, DCA and RIC for 2014 from the FAA Air Traffic Activity Data System (ATADS).

[36] *2015 State of the Commonwealth Report*. ODU, Strome College of Business, December 2015.
[37] 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
[38] 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).
[39] See above reference for obtaining 2014 NPIA data.

Table 11. ATADS-reported 2014 airport operations for ORF, IAS, DCA and RIC. (Source: FAA *2015-2019 National Plan of Integrated Airport Systems (NPIAS) Report*)

Facility	Iterant					Local			Total Operations
	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

With respect to the economic impacts of airport operations in HR and Norfolk, findings of the studies conducted for the Virginia Department of Aviation are reviewed in Section 4 of this report. Figure 13 shows the City of Norfolk's airport and heliport facilities.

DRAFT

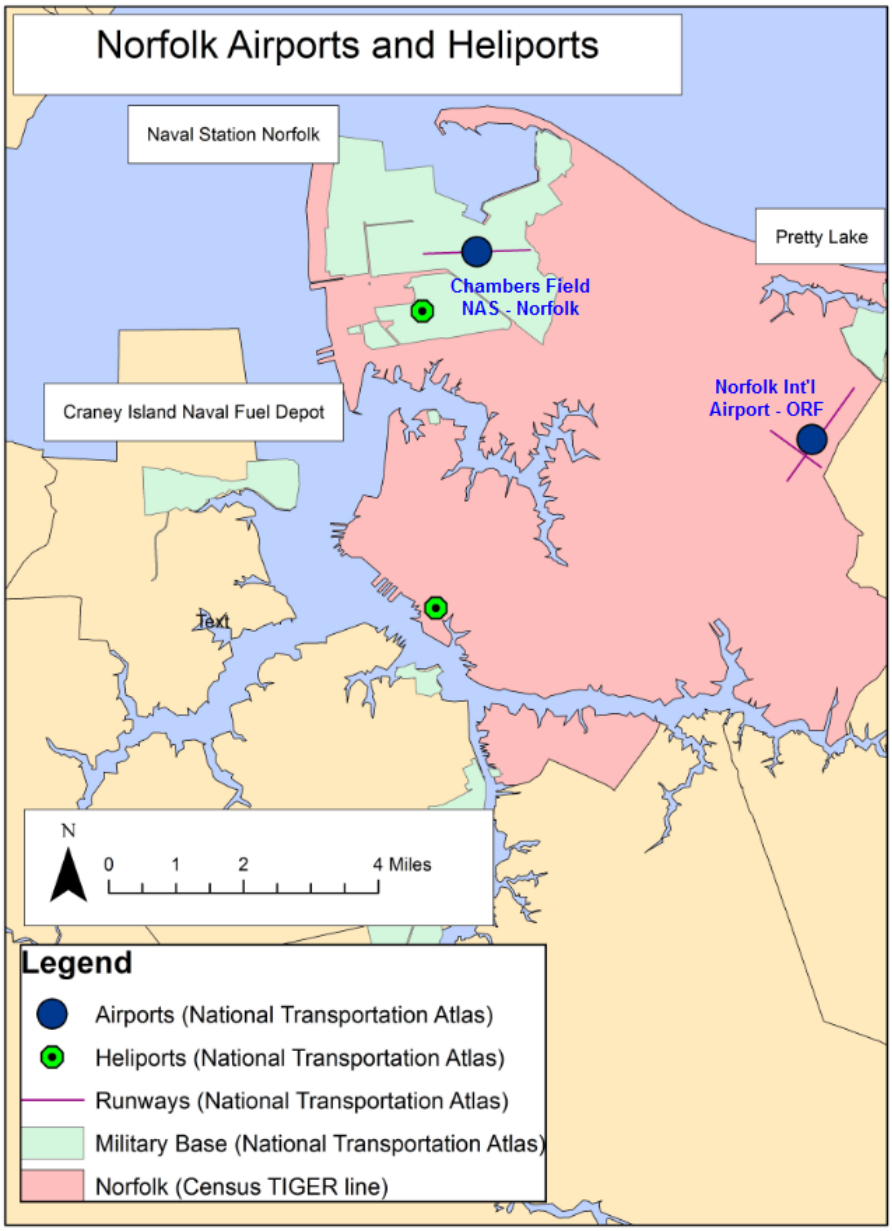


Figure 13. Norfolk Airports and Heliports (Source: NTAD)

Sea Ports

Port of Virginia (POV), the gateway for waterborne cargo flowing through the region, is managed by the Virginia Port Authority which oversees the terminal operation in HR, and owns or leases the region's four container cargo facilities: Norfolk International Terminal (NIT); Virginia International Gateway Terminals (VIG) in Portsmouth; Newport News Marine Terminal (NNMT); and Port of Richmond. POV handles no bulk coal; all bulk coal moves are handled by

private HR terminals.[40] POV ranks 7th largest in the US, and 3rd largest on the East Coast, with POV's three HR terminals—NIT, VIG, and NNMT—forming the port's hub. 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 2015 State of Commonwealth Report shows that in 2015 the Port of Virginia (POV) handled 225,988 twenty-foot-equivalent container units (TEUs), a record level compared to the 2005 rate of 164,000, and the 2009 low of 142,000 TEU. Below is a snapshot of the POV cargo movement profile:

- *The Norfolk International Terminal (NIT*) container port operates on 378 of its total 578 acres with 14 Super Post Panamax ship-to-shore cranes with capacity to move 820,000 containers, equivalent to 1,426,800 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.)

- 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% of their total capacity. In 2014, the Mason School study reports a 6.5% growth for the ports, with a record container activity of 2,305,911 TEU, equal to 90% of the combined NIT and VIG container capacity.

- *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.

[40] 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: http://www.platts.com/commodity/coal

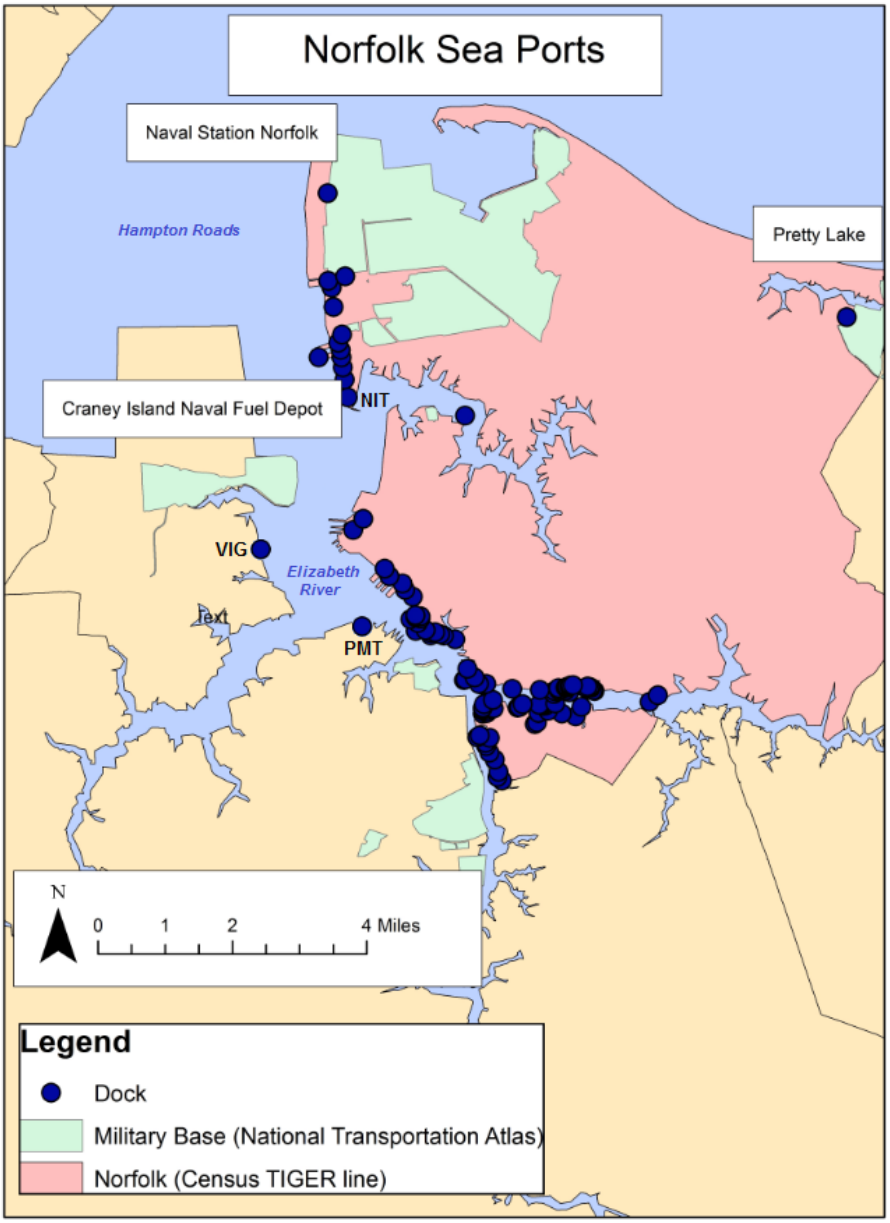


Figure 14. Norfolk Seaports. (Source: NTAD)

A key measure of port activity is the volume of cargo containers moved by export or import vessels in domestic an international trade. With a total TEU container volume, trucks carry 63% of the volume (778,316 TEI), with the remaining balance carried by rail (410,947 TEU, or 33%) and barge (53,514 TEU, or 4%). 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. Between 2013 and 2014, cargo tonnage grew to 17.53M tons (a 17% tonnage growth); while TEU volume grew 10%, reaching a record volume of 2,165,435 TEUs. Figure 15 shows the TEU container volumes by mode for the 2012-2013 time period.

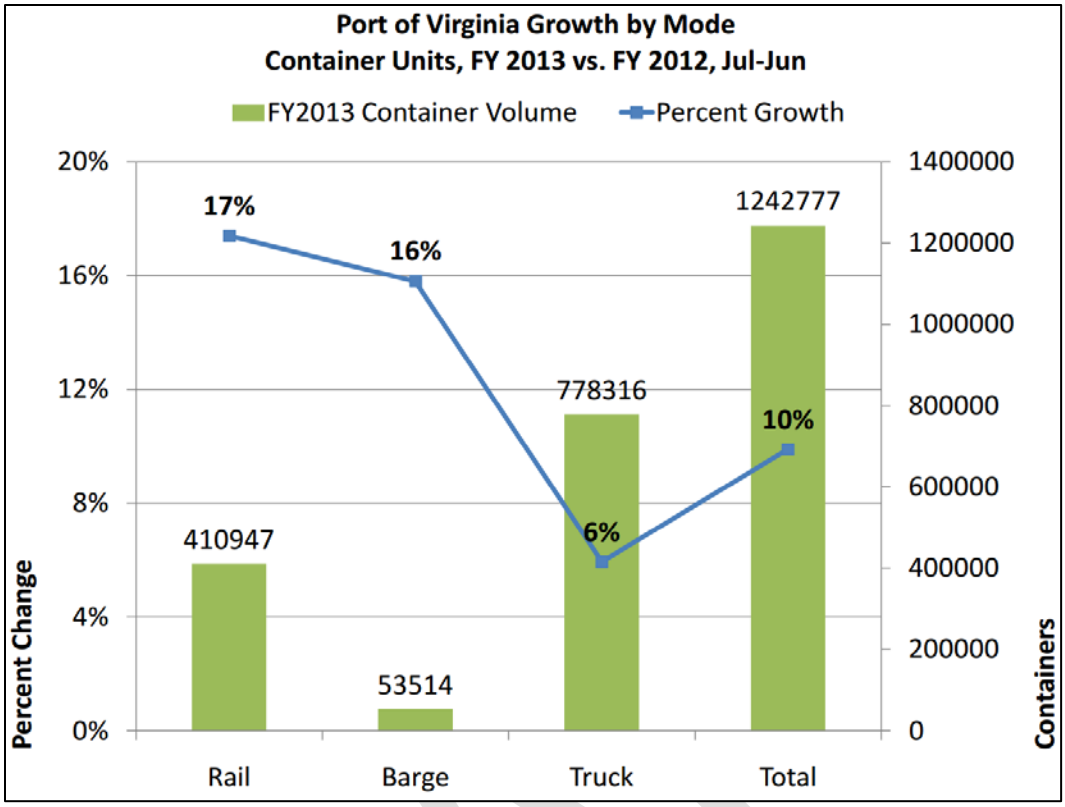


Figure 15. Port of Virginia Growth by Mode. (Source: *2013 Hampton Roads Vision Annual Report,* Hampton Roads Partnership)

Economic impacts of POV are also significant, as are the impacts of the region's airports. These impacts are reviewed in Section 4-3 of this report.

Pipelines

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.[41] Figure 16 shows pipeline assets of Columbia (in green) and VNG (in blue and red) serving HR.

[41] *2014 Virginia Energy Plan.* VA Dept. of Mines, Minerals and Energy, Oct. 2014.

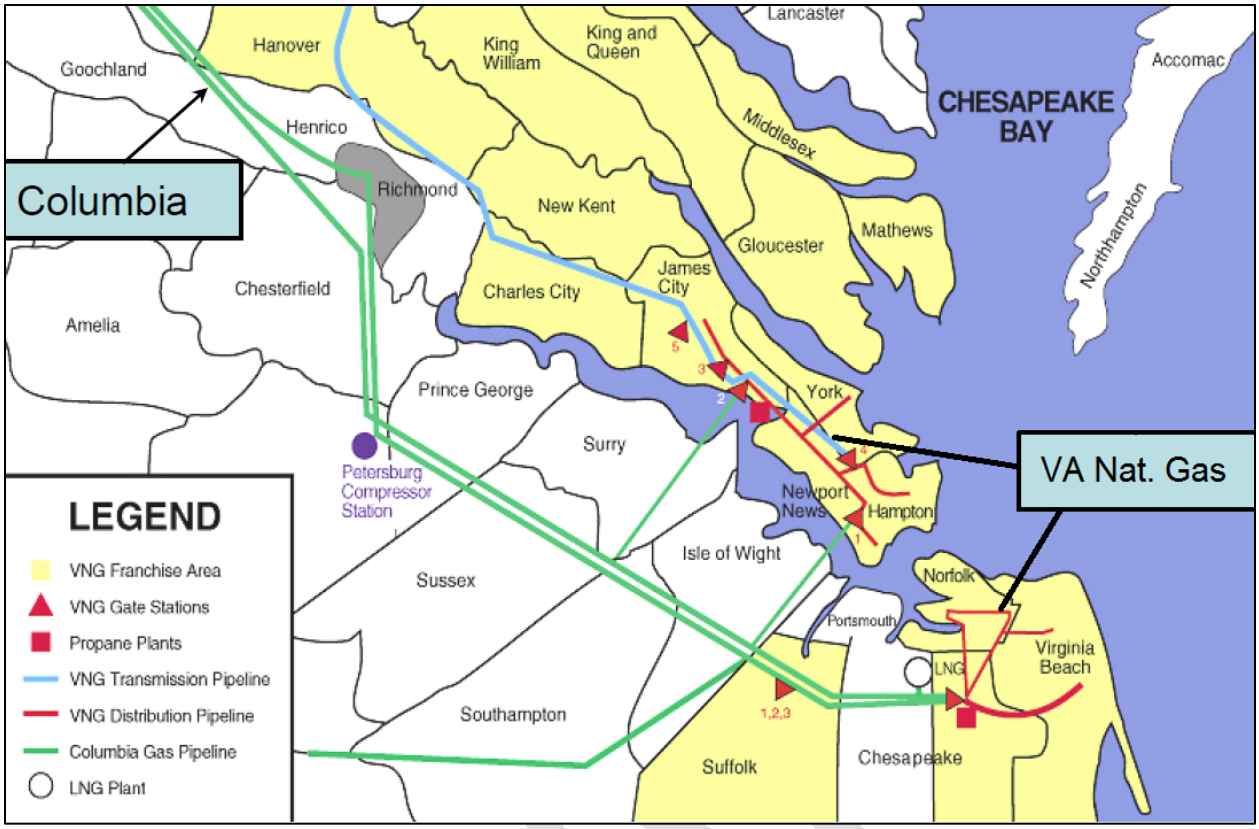


Figure 16. HR pipeline infrastructure. (Source: Virginia Natural Gas)

The geographic division created by the HR waterbody and resultant two non-contiguous gas distribution systems (Northern and Southern)[42] has 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).[43] 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 coldest heating days) fueled by propane and/or liquefied natural gas (LNG) transported in by truck.

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 17).

[42] 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.
[43] "Hampton Roads Crossing Pipeline". VA Natural Gas. See: https://virginianaturalgas.com/residential/work-in-your-neighborhood/hampton-road-crossing-pipeline

Figure 17. 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.[44] Additional asset details for the HRX pipeline follow below.

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 24" 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.

3 – Hampton Roads Climate Stressors and Approaches to Quantifying Exposure and Damage Consequences

To describe a 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. The purpose is to present a high level findings of the available studies.

[44] Ibid.

The established method for measuring risks in general is to follow a process of assessing the probability of climate-related threats; identifying infrastructure vulnerabilities and exposure levels; and calculating their consequences in terms of costs of disruption to the economy (monetized or not). For quantification of the costs of damaged transportation assets and loss of transportation service, the same standard risk assessment process, can be applied, with Text Box 1 representing a generic version of this process.

This section identifies the nature of climate stressors (Section 3-1); the conventional approaches quantifying project costs and making investment decision (Section 3-2); two representative tools for evaluating a project's broader economic impacts (Section 3-3); and Federal processes and templates for identifying and addressing vulnerabilities. (Section 3-4).

Text Box 1. Standard Risk Assessment Equation

Risk = f (Hazard Frequency *event probability;* ***x Asset Exposure*** *assets at risk of loss;* ***x Vulnerability*** *asset sensitivity;* ***x Consequences*** *$ value of losses/severity)*

where:

Hazard Frequency: measured by the probability of disruptive events caused by higher temperatures, rising sea-levels, changing precipitation, and greater severity of storms;

Asset Exposure: measured as a function of location and extent of built and natural assets; extent of coastal developments; asset engineering and construction quality, etc.

Asset Vulnerability: measured as a joint function of *exposure* and *asset sensitivity,* including aging and inadequately-maintained and protected structures; and cascading interdependencies among technology-intensive subsystems;

Consequences of Disruption: measured by metrics such as human losses (fatalities and injuries), physical asset loss (public, commercial, and residential infrastructure) and Impacts of the asset loss on the regional and national GDP, and natural/environmental resources.

3-1 Climate Stressors

Climate stressors are defined as the quantified weather and atmospheric factors that tend to cause or reinforce naturally occurring climate patterns. Changes in global sea-level and local or relative Sea-Level Rise (SLR) (influenced by interactions with local factors such as land subsidence, tidal patterns, and storm surge) are among the recognized stressors. [45] For the HR region, metrics for determining a region's vulnerability and exposure to climate risks are most commonly derived from the region's topographic position and coastal location. 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 the sea level. The following three climate-related risk factors exacerbate the threats faced by the region:

[45] Atkinkson, Larry et al. "Sea Level Rise and Flooding Risk in Virginia." *Sea Grant Law and Policy Journal* 5, no. 2 (2013).

- *Storm surge*: 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 Gauge, only slightly below the historical maximum flood of 5.26 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;[46]
- *Sea-level rise (SLR)*: The Sewells Point Gauge in Norfolk has registered an SLR of 1.5 feet (partially influenced by land subsidence) in the past century;
- *Land subsidence*: Land subsidence in HR has resulted in net loss of elevation in the region in the past decades, and has been exacerbated by groundwater withdrawal.[47]

For assessing how various manifestations of climate change impact the transportation infrastructure, this study has adopted the following definition of stressors, as summarized in Table 12. Note that the table below serves as an example of the stressors, but is not an exhaustive list covering all transportation modes.

Table 12. Climate stressors and damage mechanism on transportation infrastructure. (Source: Gulf Coast Task 3-2 –Phase 2)

Stressor	Asset type	Damage mechanism
Increased precipitation	• Culvert and storm drain network	• Flooding
SLR	• Navigable waterway bridge	• Clearance for navigation
SLR	• Bridge approach embankment	• Slope erosion
Higher storm surge	• Bridge abutment • Bridge segment • Road alignment	• Abutment scour • Wave forces/bridge pier scour • Overtopping/slope erosion
Temperature change	• Coastal tunnel • Shipping pier • Roadway pavement • Continuously welded rail	• Flooding; • Waves; Rutting; Concrete cracking • Buckling; rail pull-apart
Precipitation, wind, temperature, SLR, hurricane	• Operations & maintenance activities of various facilities	• Varies based on stressor

The exposure levels in HR to the risks of relative SLR and storm surge pose three primary threats to the region's road network, which includes:

[46] https://tidesandcurrents.noaa.gov/publications/techrpt40.pdf.
[47] Geologically, land subsidence is driven by plate tectonics of post-glacial isostatic adjustment.

a) Flooding of evacuation routes;
b) Increased hydraulic pressure on tunnels; and
c) Alteration to drainage capacity.

Among the tools available for measuring some of these stressors are those developed by NOAA and VIMS for identifying climate stressors in HR.

NOAA has developed models for estimating the likelihood of severe weather events in HR and evaluated the region's tidal patterns and exposure and vulnerability to SLR and storm surge. The Sewells Point Tide Gauge for predicting SLR and storm- surge is one such tool that served as a technological transition point marking the historical switch from reliance on proxy records of SLR to today's tide gauges and satellite receivers. Trend data on historical projections of SLR levels between 1800 and 2100, and projections of the rise in sea levels from 1 to 4 feet by 2100 are depicted in Figure 18, showing that since mid-century satellite signals have improved the overall precision of data.[48]

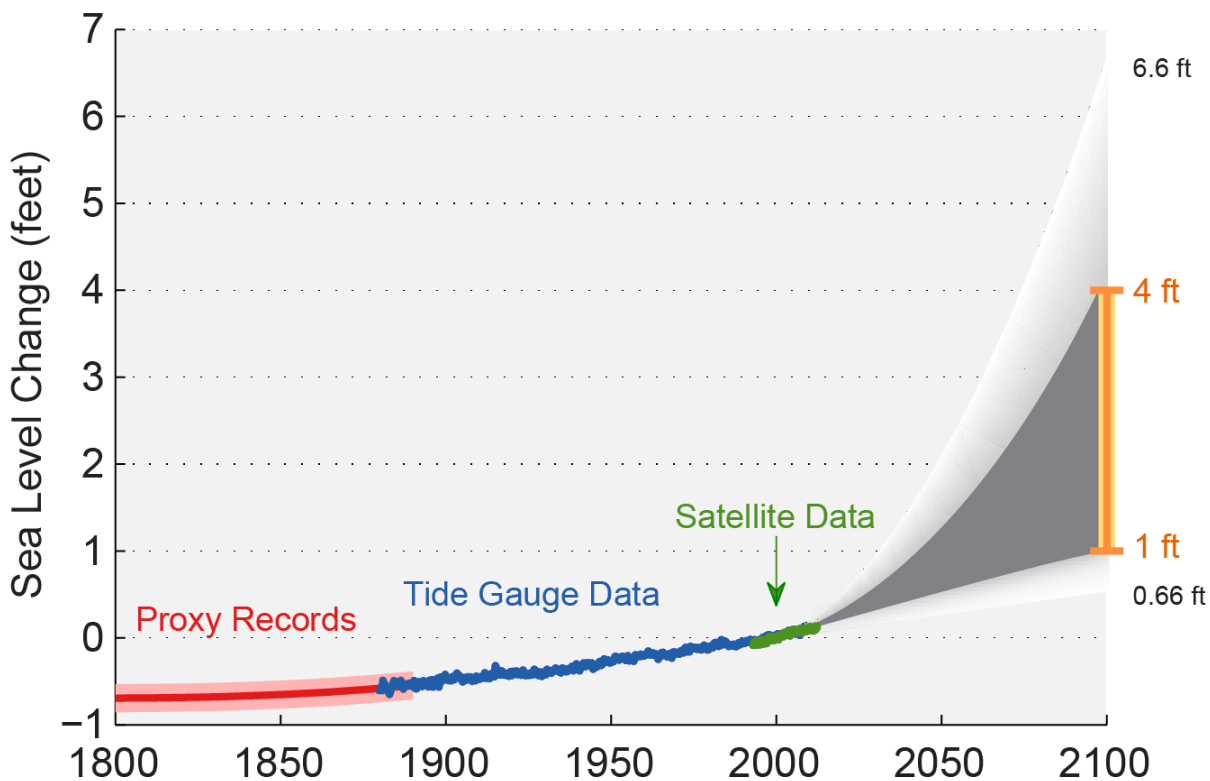


Figure 18. SLR projections, 1800 – 2100. (Source: U.S. Global Change Research Program)

[48] Melillo, Jerry M., Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program.

As measured by NOAA's tide gauge, Virginia has had the highest rate of measured SLR over the last 100 years of all states on the East Coast. The Sewells Point Tide Gauge in Norfolk has recorded a centennial rate of 0.44 meters (1.45 feet).[49] Based on this trend on SLR, some regional studies have predicted that, for the next 100 years, Norfolk's rate of SLR will rise between a minimum of 0.44 meter to as high as 0.7 meters (2.3 feet).[50]

The tool NOAA has developed for predicting storm surge—the *Sea, Lake, and Overland Surges for Hurricanes, or SLOSH* model—is among the many models currently in use for measuring storm surge. The NOAA National Weather Service (NWS) and National Hurricane Center (NHC) have developed the SLOSH model as a computerized numerical tool to estimate storm surge heights resulting from historical, hypothetical, or predicted hurricanes by taking into account the atmospheric pressure and other parameters to create a model of the wind field which drives the storm.[51]

With the growing recognition of the risks of SLR threatening the Virginia coastal areas, the Virginia Institute of Marine Science (VIMS) has developed tools for estimating relative SLR risks to close some of the gaps in the use of climate data for long term project planning, including its absence in the HR 2035 Long Range Transportation Plan (LRTP). VIMS researchers have calculated the probability of an SLR of 4.25 mm per year with a 95% confidence interval of 0.27 mm. VIMS has used its tools to identify the segments of the Virginia coastal areas (known as the "Tidewater") that are exposed to recurrent flooding of the roadways. VIMS trend data have indicated that between 1927 and 2006, HR experienced a total of 1.15 feet of "relative SLR," as measured by the Sewells Point Tide Gauge location on Naval Station Norfolk. VIMS analysis indicates an acceleration of the rate of the relative SLR from the Mid-Atlantic to New England. Land subsidence in HR has also been a contributing factor, as noted above. Estimates for the range of relative SLR have been from 1.6' to 7.5' between 1992 and 2100 for Sewells Point based on four global SLR scenarios developed in 2013. VIMS has recognized that models such as NOAA's SLOSH have a degree of uncertainty as to the precise level of variation in SLR; and they have recommended that the coastal communities use the tool as an "Early Warning System" for regional emergency response and recovery (R&R) managers.[52]

---

[49] Stiles, William A. "A "Tool Kit" for SLR Adaptation in Virginia." *Wetlands Watch* (undated report).

[50] Pyke, et al. *Climate Change and the Chesapeake Bay, State-of-the-Science Review and Recommendations*. Science and Technical Advisory Committee (STAC), Annapolis, MD., 2008.

[51] 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

[52] *Recurrent Flooding Study for Tidewater Virginia.* Virginia Institute of Marine Science (VIMS), Center for Coastal Resource Management, William and Mary University, Jan. 2013.

Based on the three factors—Rising Risks of SLR, Storm Surge, and Land Subsidence— and given the uncertainty about SLR and how fast it will accelerate, VIMS research concluded that 1.5 feet of SLR could occur in HR sometime between 2032 and 2065. In the context of the challenges of arriving at accurate estimates for the region's 2040 long-range forecast-year, the VIMS report notes that during Hurricane Irene in 2011, the Sewells Point gauge measured a storm surge of 4.2'; and a storm-surge of 4.4' during Hurricane Isabel in 2003. A combination of these two historical storm surges confirmed the VIMS's recommendation that a 4.5' SLR/Storm surge level be considered as a baseline for future planning. To show the region's vulnerability to a total rise of 4.5', based on the predicted relative SLR of 1.5' plus a storm surge of 3', VIMS created a summary table of all coastal locations in coastal Virginia vulnerable to such a rise in water level. Table 13 shows the levels of vulnerability at several HR jurisdictions.[53]

Table 13. Top 7 HR Jurisdictions with vulnerability to a rise in water level of 4.5' (based on SLR of 1.5' and storm surge of 3'). (Source: *Hampton Roads Military Transportation Needs Study: Roads Serving the Military and Sea Level Rise/Storm Surge*, HRPTO, July 2013.)

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%	460	15

*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;

Table 13 above underscores the high level of 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% of Norfolk's total acres (4,167acres) has the potential to flood, in reality 60% of these acres in vulnerable area are developed parcels (a total of 2,500 acres and 119 miles of road), thus making a significant part of the city's structures exposed to flooding from sea level rise. This contrasts with Poquoson, where 69% of its acres

[53] The data, as reported by HRTPO, are based on the benchmarks derived from the VIMS report on *Recurrent Flooding Study for Tidewater Virginia*.

have the potential to be flooded, but with only 11% of the land developed, only 750 acres of the developed acres are likely to be flooded.[54]

Exposure risks for Norfolk's highway infrastructure are also higher than the rest of the HR region. Table 14 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 the mid-level estimates). The table shows that about 7% of Norfolk's total road miles, and 9% of its interstate highway links are at risk of flooding from a 1-meter SLR, compared to 4.3% and 5.6%, respectively, for the HR region.

Table 14. Exposure to one meter of SLR above spring high tide in Hampton Roads and Norfolk. (Source: HPRDC)

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
Primary	1,460	50	6.5	152	9	0.6
Secondary	2,216	72	3.2	0	0	-
Local or Private	7,841	371	4.7	943	12	1.3
Total Road-miles	**11,767**	**507**	**4.3**	**1,150**	**76**	**6.6**

3-2 Quantifying the Consequences: Conventional Methods for Measuring the Impacts of Climate Events

Consequences of a hazardous climate event can be fatalities and injuries, which have straight forward ways of measuring. Consequences can also be tangible effects such as traffic delays or non-tangible effects such as environmental/quality of life degradation. Or the consequences can be the economic costs incurred. All these consequences—tangible or non-tangible—can be directly quantified and monetized.

This section reviews the conventional methods used by transportation agencies for quantifying three types of climate consequences:

[54] 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.

- Transportation-related cost of adverse event—safety, traffic delays, and network disruptions costs and consequences are commonly measured through methods such as net present value (NPV) of benefits, cost-effectiveness/lifecycle costs (LCC) or benefit-cost analysis (BCA);
- Economic impact analysis (EIA) is conducted to assess full direct and indirect costs and benefits of transportation projects for investment decision and asset management;
- Input-output (I-O) models used by transportation agencies for estimating the full impacts of adverse climate events or transportation investment, and determination of long-term impacts on the regional economy.

Measuring Transportation Costs of Adverse Events

The most common tools used by transportation planning agencies include those for calculating the present value (using NPV) of a project; its life-cycle costs (using LCCA), or its benefit-cost balance (using BCA). The FHWA *Economic Analysis Primer* is a key source of information on the metrics that go into deciding what constitutes costs and benefits in a transportation investment process.[55] The Primer describes how the following metrics are quantified for transportation cost analysis:

> *Agency costs:* These include expenditures for design & engineering, land acquisition, reconstruction and rehabilitation, routine maintenance, and applicable mitigation measures (e.g., noise barriers);
>
> *User costs:* These are the costs associated with facility operations: travel time and delay, crashes, and vehicle operating costs (VOC). Also included are the user costs associated with work-zone delays, crashes and VOC, (and in some cases the costs also include applicable non-user costs such as emissions and noise). User benefits are defined as the avoided costs resulting from the improvement projects.

Through these two metrics, transportation analysts measure the project costs and benefits by calculating the value of C as the sum of agency costs; and value of B as the user benefits (as the sum of all avoided user costs). Next, the results are used to calculate the following metrics:

- Net Present Value of Benefits (NPV) – This metric calculates the present value (PV) of all benefits and costs of a project's lifecycle, discounted to the present; the costs are

[55] *Economic Analysis Primer.* FHWA, 2003.

subtracted from the benefits to yield a NPV. If B exceeds C this measure is positive and project worth pursuing.

- *Benefit-Cost Ratio (BCR)* – This measure places the PV of benefits (minus the negative values) in the numerator of the ratio, and the PV of the initial agency investment cost in the denominator. 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.

- *Life-Cycle Cost Analysis (LCCA)/Cost-Effectiveness Analysis* – LCCA and cost-effectiveness methods are used when an agency attempts to determine the lowest life-cycle costs as the most cost-effective means to accomplish the projects; under conditions that the benefits are assumed to be equal among all projects. When the benefits vary across projects, then instead of LCCA/Cost-Effectiveness method, a BCA will need to be conducted (see below). As a cost-only subset of BCA, LCCA considers value engineering to improve project design to select the most affordable means of accomplishing the same goal.

- *Benefit-Cost Analysis (BCA)* – This method is used in project investment cases when the alternatives do not generate identical benefits. The BCA is used to quantify both LCCA B and C, through a process that: establishes the *base case;* identifies alternatives; sets an analysis period; analyzes traffic effects; estimates B and C for the *base case*, evaluates risk; compares net benefits; ranks alternatives; and makes recommendations. The *base case* calculated in a BCA relates to the "do minimal option"; it represents the continued operations of the current facility under good management practices but without major investment. 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.

The FHWA *Primer* has recognized the limitations of the conventional BCA, NPV and LCCA methods for determining transportation network costs and benefits. It points to the pitfalls of these methods, 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 FHWA has recommended that two improvements be made to the process of cost analysis:

a) 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

b) 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.[56]

Using the EIA Methodology to Evaluate Consequences of Transportation Projects or Events

Having recognized some of the pitfalls of conventional BCA and LLCA methods of calculating project costs and impacts, FHWA has more recently begun incorporating broader indirect measures of economic and climate-change impacts on the transportation infrastructure performance and costs. For this FHWA has incorporated two major approaches to transportation investment needs: First, the need to conduct *Economic Impact Analysis* (EIA) to measure the direct as well as indirect impacts of transportation assets. Second, the need to incorporate climate considerations into the conventional Transportation Asset Management (TAM) methodology to consider both the direct travel time impacts and the secondary impacts on transportation demand and shifts in economic activity resulting from climate change.[57] The elements of the TAM initiative are examined below in Section 3-3.

Economic Impact Analysis (EIA) – EIA is a study of the way in which the direct benefits and costs of a project affect the local, regional employment patterns, wage levels, business activity, tourism, housing and even migration patterns (it should not be confused with the environmental impact analysis mandated by NEPA). 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 averted. These models capture not only the first-order multiplier effects when the project funds are spent, but also the second round of multiplier effects as the output impacts of the improvements filter through the region (see discussion below on I-O models). EIA models improve on the conventional LCC and NPV since they integrate travel demand models, land-use, and dynamic input-output economic interaction.

The advantage of EIA is that it generates superior results compared to BCA. While BCA measures the direct benefits and costs of a single project for a transportation agency (with

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

[57] *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I.* U.S. Climate Change Science Program and the Subcommittee on Global Change Research, 2008.

direct costs defined as first order or immediate impacts of a project on users and nonusers (in cases where externalities are present); BCA does not measure how these direct costs and benefits are converted into indirect effects on the economy (jobs, land use, etc.). These indirect effects take place through the operations of the market place and are assumed to have the same monetary value as the BCA values.

The FHWA *Economic Analysis Primer* emphasizes that the value of most converted economic effects in an IEA is not additive to the value of BCA-measured direct effects; rather the EIA effects are often a restatement or capitalization of the value of the benefits captured in BCA. Faster commuting time, 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. As the need for greater precision and analytical breadth of BCA tools grows, more sophisticated EIA studies are done with I-O models that capture aggregate regional economic effects.

Measuring Economic Impacts of Transportation through I-O Models

I-O models are readily available economic analysis tools that enable consideration of broad range of direct and indirect economic impacts resulting from an infrastructure disruption. Input-Output models such as RIMS II and 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 allow focusing on specific segments of the transportation network, ports, rail facilities, power stations, etc., at the regional or sub-metropolitan level.[58]

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 output by NAICS (North American Industry Classification System) industry class. Using these data, I-O models such as RIMS II, IMPLAN, and 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.

Notwithstanding the acknowledged advantages of EIA tools over simple LCCA or BCA methods, researchers need to keep in mind that the EIA and I-O model results should neither state nor imply, however, that the monetary value of indirect economic effects is additional to the NPV

[58] 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.

measured in the BCA. To do so would overstate the economic justification of the project by effectively double counting the project's net benefits, as the FHWA Primer points out.[59] These broader applications of IEA apply to projects considered in response to climate-change impact, as discussed below in the context of TAM and CAPTA/CAPTool.

Appendix D describes the I-O models and the Computable General Equilibrium (CGE) methodology. Section 4-2 reviews Sandia's I-O tool, REAcct, with estimates of direct and indirect economic impacts in Norfolk.

3-3 Tools for Managing Transportation Assets and Addressing Economic Impacts of Climate Change

Several useful tools have been developed in the past decade to address the economic impacts of climate change on transportation assets, among them the FHWA tool for risk-based asset management and the NCHRP CAPTA tool, as reviewed in this section.

Transportation Asset Management (TAM)

For decades, FHWA has been conducting transportation asset management (TAM) as part of the agency's 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. A remark made in a 2012 IPCC report marks this turning point in our perspective:

> *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*. [60]

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.[61] TAM's applications for managing climate 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-

[59] FHWA Primer, 2003.
[60] Field, Christopher B., et. al. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: A Special Report of the IPCC.* Working Groups I & II, IPCC. (2012).
[61] *Risk-Based Asset Management: Managing Risks to Networks, Corridors, and Critical Structures; Report 4: Managing Risks to Critical Assets*. FHWA, March 2013.
Risk-Based Transportation Asset Management: Building Resilience into Transportation Assets: Report 5: Managing External Threats Through Risk-Based Asset Management. FHWA, March 2013.

management responsibilities. 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.[62]

FHWA TAM reports have pointed out that the steady increase in federal outlays required to pay for damages for natural and climate-related disasters have to a large extent driven the move to a systematic risk- and resilience-based approach to Federal/state agencies to their short-term as well as long-term transportation planning. The report noted that the Federal disaster recovery expenses for the 1994 Northridge Earthquake amounted to $11.6B, compared to $50B for the 2012 hurricane Sandy. FHWA has emphasized the research findings indicating the impacts of adverse events are inversely proportional to the degree of preparedness or resilience in a community. FHWA cites the results of the Multi-Hazard Mitigation Council (MMC) study that found that, between 1993 and 2003, total community-wide benefits from preventive and mitigation actions yielded a discounted present value of $14B, compared to the $3.5B the value of resources employed in the hazard mitigation program; concluding that for each 1$ spent on mitigation, $4 was generated in benefits.[63] The study was conducted by the MMC, a member of the National Institute of Building Sciences, through a grant from FEMA to quantify the future savings from hazard mitigation activities.[64] Using HAZUS-MH database to estimate direct property damage from earthquake and hurricane winds, the study estimated the future savings from FEMA mitigation grant expenditures, using a statistically representative sample of FEMA-funded mitigation grants so that results could be generalized to the entire population of FEMA mitigation grants.[65]

---

[62] Michael Meyer (ASCE), et al. *Integrating Extreme Weather Risk into Transportation Asset Management*. AASHTO, Nov. 2012.

[63] One of the MMC case studies related to the 1997 Red River flooding in Grand Forks, North Dakota, which flooded 8,600 homes and caused $3.7 billion in damages. Following this 1997 disaster, the state, local government, and FEMA worked together to buy nearly 700 of the most vulnerable homes with FEMA mitigation grant funding. The Red River flooded again in 2006, yet the losses were kept to $6.5 million.

[64] *Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities, Volume 1 – Findings, Conclusions, and Recommendations.* Multi-hazard Mitigation Council, National Institute of Building Sciences, 2005. The study was conducted in response to a mandate by the House Appropriations Committee, of the 106th Congress (House Report 106-161) for stepped up preventive structural maintenance.

[65] These savings were estimated for both "project" mitigation, i.e., physical and engineering measures built, and "process" mitigation relating to community practices such as adoption of building codes, land-use restrictions, and conducting RA to reduce vulnerabilities.

The NCHRP CAPTA/CAPTool: A Consequence-Based Risk Management Tool

The NCHRP tool, Costing Asset Protection for Transportation Agencies (CAPTA or CapTool), is an asset management tool that provides a set of guidelines for identification of critical or high-cost assets and evaluation of the potential countermeasures.[66] The tool, released in 2009 by NCHRP, uses a standard risk model *R = f (T, V, C)* for quantifying threats, vulnerabilities, and consequences to measure the community's relative susceptibility to the consequences of hazards.

A key component of CAPTA is its "Consequence Threshold,"—which calculates the capacity of an asset to exceed the threshold—for evaluating a broad range of natural and man-made hazards. The threshold is determined by the user, with guidance from sources such as the National Fire Protection Association, FEMA's National Flood Protection Act (NFPA) guidelines, or other engineering standards. CAPTool's 6-step structure, as described below, underscore the critical role of linking Consequence Threshold (Step 2) and the Countermeasure Opportunities (Step 5), leading to the final Step 6 that incorporates the full range of decision factors.[67]

Step 1. Identify Asset Threats/Hazards – For each asset class (road bridges, road tunnel, rail/transit bridges and tunnel, support facilities, ferry, port fleet) threats—flood, extreme weather, mudslide, structural failure, etc.—are identified on the database;

Step 2. Establish Consequence Thresholds – This is defined as the threshold beyond which the asset owner, operator or system user would consider investments in countermeasures to prevent losses, or mitigate consequences. This step determines what level of risk to the *population, property loss, or service/mission disruption* to the asset can be addressed in the agency's current operations, and helps determine which assets are deemed critical and require further attention:

- **Potentially Exposed Population (PEP):** This is defined by the potential casualties from the disruption, indicating a threshold determined as the upper bound on the limits of hardship on people associated with the threat; it is determined by the extent of potential exposure to extreme levels of risk, rather than an estimate of the actual casualties.

[66] *Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA),* Report 525, Surface Transportation Security Volume 15. NCHRP, 2009.
[67] *CAPTool User Guide: Using CAPTool to Implement the "Costing Asset Protection: An All-Hazards Guide for Transportation Agencies."* FHWA, Jan. 2013.

- **Property Loss:** Threshold for asset replacement costs (in $million across the cost range).
- **Mission Importance:** This is expressed in terms of loss of assets function and/or attendant transportation delays; the mission importance is determined for each specific assets or asset classes; (for instance ADT and detour distance may be used as a surrogate for mission or function impact; users may set 75%, 85% or 95% percentile based on the National Bridge Inventory.)

Step 3. Describe Infrastructure Assets – Describe infrastructure assets, their network attributes, operational properties, capacity, and function.

Step 4. Identify Critical Assets Across Modes – Describes the functional requirements and operational capacity for road bridges, road tunnels, transit/freight rail stations, transit/freight rail bridges, transit/freight rail tunnels, support facilities, ferries, and fleet vehicles.

Step 5. Identify Countermeasures – This step selects a range of potential countermeasures that the tool has embedded in the dictionary; includes prediction/intelligence gathering, detection, interdiction, response/preparedness, design/engineering measures. For natural hazards these countermeasures include barriers/berms; retrofitting, easement, and asset redundancy. Countermeasure costs determined in the CAPTool by using logical cost assumptions from the RSMeans cost estimating manual.[68]

Step 6. Results Summary – This module displays the "inputs" (e.g., relative risk and thresholds), and the "results" (e.g., the number of critical assets and countermeasure expenditures for each type of asset). This step compares the results for different set of inputs and thresholds, it emphasizes that setting threshold is an iterative procedure based on the budget and criticality of each asset; often contingent on the share of expenditures and the user constraints that will refine the thresholds.

A recent application of the CAP Tool has been a case study by a research team at the University of Delaware. The team found the "consequence-based" approach of CAPTA tool a useful enhancement of conventional risk analysis models that focus on estimating threat-probability. The researchers noted that the difficulty of estimating the frequency and likelihood of adverse events makes CAPTA a preferred tool for climate-related risk analysis. They noted that the tool potentially incorporates the key features of Haimes' Inoperability/Risk Filtering model (as

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

reviewed in Section 4-3 as the underlying tool adopted by the Gulf Coast 2 Pilot, for assessment of climate risks). The researchers emphasize that the advantage of a consequence-based approach is that if the consequences are sufficiently severe, the decision-makers would consider alternatives for avoiding or minimizing the potential consequences, given the chosen threshold, a point beyond which the effects of routine disruption and losses become unacceptable.[69] Table 15 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.

Table 15. CAPTA Consequence Threshold. (Source: *Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA), Report 525;* NCHRP, 2009)

Asset	PEP Equation	Property Equation	Mission Equation
Road Bridges	Classed by primary/secondary; (if vehicle/lane >2400 assume 40 vehicle/1000; if lower assume 7.5 vehicle/1000)	$20,000/lane feet	ADT x detour length (75th, 85th, 95th percentile as threshold relative to typical BNI bridge inventory)
Road Tunnels	Similar to above	$100,000/ft	User input for criticality
Transit/Rail Station	4 x max capacity of rail cars	Below ground = critical	User input if transfer station
Transit/Rail bridge	2 x max capacity or rail car	$15,600/ft	User input % ridership
Transit/Rail tunnel	2 x max capacity of rail car	$40,000/ft	User input % or ridership regularly using asset
Support Facilities	1 person/175 sq. ft	$210/sq. ft	Never critical unless so designated by user
Ferries	Max ferry capacity	User input	Never critical unless so designated by user
Fleet Vehicles	Max occupancy of one fleet vehicle	Avg. cost per vehicle/max # of vehicles	Never critical unless so designated

3-4 Federal Processes and Templates for Streamlining Assessment of Transportation Infrastructure Risks

[69] S. Rahimian and Sue McNeil. *Infrastructure Security and Emergency Preparedness: Selecting Asset Protection Strategies*. Delaware Center for Transportation, University of Delaware, June 2012.

Many standard processes are in place for assessing the risks threatening the transportation network and the surrounding region. The processes include an integration of the regional climate models scenarios for assessing climate events' probability and damage functions, adaptation alternatives, and the economic models that help determine the payoff of adaptation measures. This section provides examples from the USACE and DOT/FHWA, EPA's CIRA, NOAA's Coastal Resilience Index and Social Vulnerability Index (SOVi), and NASA's CASI tools and processes for assessing risks to transportation assets.

USACE Infrastructure Risk Management Tools

The USACE has in place several standard processes and risk-mitigation practices for addressing infrastructure risks of inland waterways and coastal marine transportation assets. One example of the risk-reduction strategy is the agency'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. By one estimate, the USACE risk mitigation processes may have potentially reduced flooding damages by $140B. Table 16 and Figure 19, below, depict the 5-step 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.

Table 16. USACE Process for Assessing Flood Risks, Vulnerabilities, and Consequences of Alternatives

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
3 – *Building Codes*	New building standards, incorporation of climate change/SLR into codes and standards
4 – *Insurance*	Flood plain mapping, annual flood risk notification
5 – *Levees*	Critical levee repair projects, improved maintenance and inspection, levee area evacuation plan, mitigation banking, climate change adjustments to flood hydraulics
6 – *Residual Risk*	Financials costs and consequences of damages

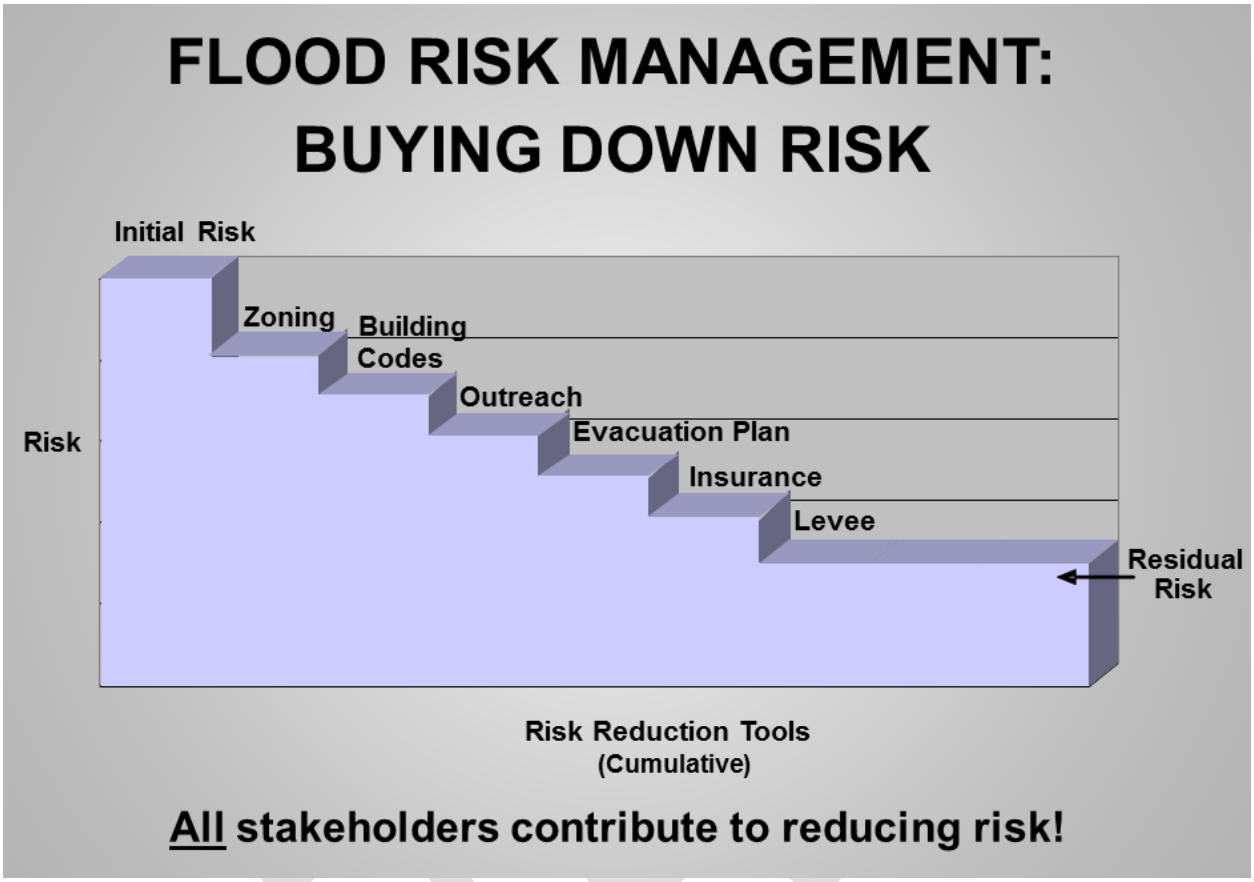


Figure 19. USACE depiction of incrementally reducing risk through various countermeasures. (Source: USACE)

In Hampton Roads, USACE has been implementing a multi-layered risk-management (RM) program, with a special focus on the defense facilities located in Norfolk. The Norfolk project team has been conducting a study to address the risks of coastal storm and SLR in Norfolk based on a strategy that: selects project through an analysis of cost and performance data in the agency's coastal investment portfolio to manage "*regrets*"; making decisions based on return-on-investment (ROI); and considering long-term infrastructure resilience and sustainability.[70] The USACE RM strategy, referred to as SMART—Specific, Measurable, Actionable, Relevant, and Time-based—consists of the following building blocks:

Specific: Specified goals for stakeholders, location and operations;

Measurable: How much is enough? What level of confidence is needed?

Actionable: Will the results of actions be meaningful and useful?

[70] Burkes-Copes, K. et al. *Risk Quantification for Sustaining Coastal Military Installation Asset and Mission Capabilities*. U.S. Army Engineers R&D Center (ERDC), Oct. 2014.

Relevant: Does the effort match the ROI?

Time-based: What should be done immediately? What actions can we wait for? How long before the threat becomes critical?

For addressing the Norfolk defense infrastructure risks and managing its flooding risks, the SMART model operationalized the following components of the area's SLR and climate change risks:

Exposure	The nature and magnitude of the hazards that threaten the systems critical assets and its functions;
Sensitivity	Potential of a system to be affected (positively or negatively) by the changes caused by a hazard;
Adaptive Capacity	Ability to evolve either naturally or through engineered maintenance activities in such a way as to preserve/enhance the functionality;
Vulnerability	*Vulnerability = exposure + sensitivity + adaptive capacity;* measured as the degree to which a system is susceptible to, and unable to cope with adverse effects of hazards over a period of time;
Risk	An overarching concept incorporating components of hazard and impacts on performance attributed to climate change impacts: a combination of exposure, vulnerability, the magnitude of the potential consequence(s); and the likelihood that the consequences will occur;
Resilience	Ability of a system to prepare for, resist, recover, and adapt to achieve functional performance under the stress of natural/human-made hazards through time.

The output of the SMART model enabled the USACE researchers to prioritize the engineering projects under consideration by evaluating the metrics that ranked candidate assets and project according to the following criteria:

- Degree to which assets are exposed to coastal hazards;
- Susceptibility to SLR (e.g., asset elevation levels);
- Presence of unique or significant/scarce assets and capabilities;
- Potential for coast shoreline change and increased exposure;

- Potential for contaminant release from installation.[71]

FHWA/VDOT Process for Conducting Regional Risk Assessment

DOT's Climate Resilience Toolkit, developed in response to the President's *Climate Action Plan*, has identified a set of tools and information resources, including the Climate Data Initiative (CDI).[72] Included among FHWA tools are the Haimes Inoperability/Risk Filtering model, the VAST vulnerability assessment tool, and the MCDA process, as described below.

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

Included among the risk-assessment toolset deployed in the Gulf Coast 1 Pilot project, was an 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.[73] FHWA and VDOT have adopted Haimes' framework for evaluation of the HR Pilot findings. His multi-component model provides serves as an overarching conceptual framework for risk assessment. 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, called the *Inoperability Input-Output Analysis (IIA) Model* -- based on the Leontief method for computing economic I-O relationships—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-

[71] Ibid.

[72] "U.S. Climate Resilience Toolkit." See: http://toolkit.climate.gov

The Climate Data Initiative (CDI) is a broad effort to leverage freely available federal climate data resources to stimulate innovation and private sector entrepreneurship. See: https://www.whitehouse.gov/blog/2014/03/19/climate-data-initiative-launches-strong-public-and-private-sector-commitments

[73] Haimes, Yacov Y., et al. *Assessing and Managing Risk of Terrorism to Virginia's Interdependent Transportation Systems*. Center for Risk Management of Engineering Systems (CREMS), University of Virginia, October 2004.

destination trips disrupted, with the scale 0 representing "*operations as planned*", and 100 as total loss of network functionalities.)

- The "*economic loss"* measure: 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. The term "holographic" here refers to a multi-view image of a system (as opposed to a single, planar image) to identify a broad range of vulnerabilities. It captures the bi-directional interdependencies among 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. 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?

Risk Filtering builds on the HHM to identify risks, then filters and ranks the many sources of risks, enabling decision-makers to focus on those that are most critical. Next the prioritized risks are further considered in 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.

Risk filtering and priority ranking serves as a qualitative framework. While qualitative screening of scenarios and classes of scenarios is appropriate initially, quantitative assessments may be applied once the set of all scenarios (potentially hundreds) has been prioritized in several phases. Haimes' methodology reflects an initial assessment approach rather than a mechanical methodology. In this approach, the process of filtering and

ranking of discrete scenarios is viewed as a precursor to, rather than a substitute for, consideration of the totality of all risk scenarios. This eight-phase methodology is described in detail and is applied to many risk management operations.[74] The risk-filtering process consists of the following phases:

1. Scenario identification through HHM;
2. Scenario filtering;
3. Bi-Criteria filtering and rankings;
4. Multi-criteria evaluation
5. Quantitative ranking;
6. Risk management;
7. Safeguarding mission critical items;
8. Operational feedback.

Many methodological and data analytical discussions on transportation climate risks in this report address some of the principles inherent in Haimes' risk assessment framework, including the applications of the model in the Gulf Coast 2 and the MCDA process in the HR Pilot.

The VAST Tool

The Vulnerability Assessment Scoring Tool (VAST) has been developed by FHWA for use by planners and asset-managers to select climate *stressors* and vulnerabilities for each asset type.

Vast is a component of the FHWA Virtual Climate Change Adaptation Tools Framework. The site went live in 2014 as the FHWA Climate Change Adaptation site. VAST has six modules: Module 1 – articulate objectives; Module 2 – identify climate stressors (variables) and develop a transportation asset sensitivity matrix; Module 3 – select and characterize assets; Module 4 – assess vulnerability (using CMIP Climate Data Processing Tool);[75] Module 5 – integration into decision-making, and; Module 6 – monitor and revisit.[76]

VAST identifies *exposure levels; asset sensitivity* and *adaptation capability;* and produces a *scoring dashboard* to reflect the scale of threats and mitigation measures. The tool requires that asset managers collect a range of data for the vulnerability assessment, including: age of asset; geographic location; elevation; current/historical performance and condition; level of use

[74] Haimes, et al. October 2004.

[75] The U.S. DOT Coupled Model Intercomparison Project (CMIP) Climate Data Processing Tool will process raw climate model outputs from the World Climate Research Programme's CMIP3 and CMIP5, into relevant statistics for transportation planners.

[76] "Virtual Framework for Vulnerability Assessment." FHWA.

See: http://www.fhwa.dot.gov/environment/climate_change/adaptation/adaptation_framework/modules

(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; and a vegetation survey. The data collection process is undertaken within a framework that first identifies the vulnerability of transportation assets, followed by development of a scoring tool for measuring their severity (Figure 20).[77]

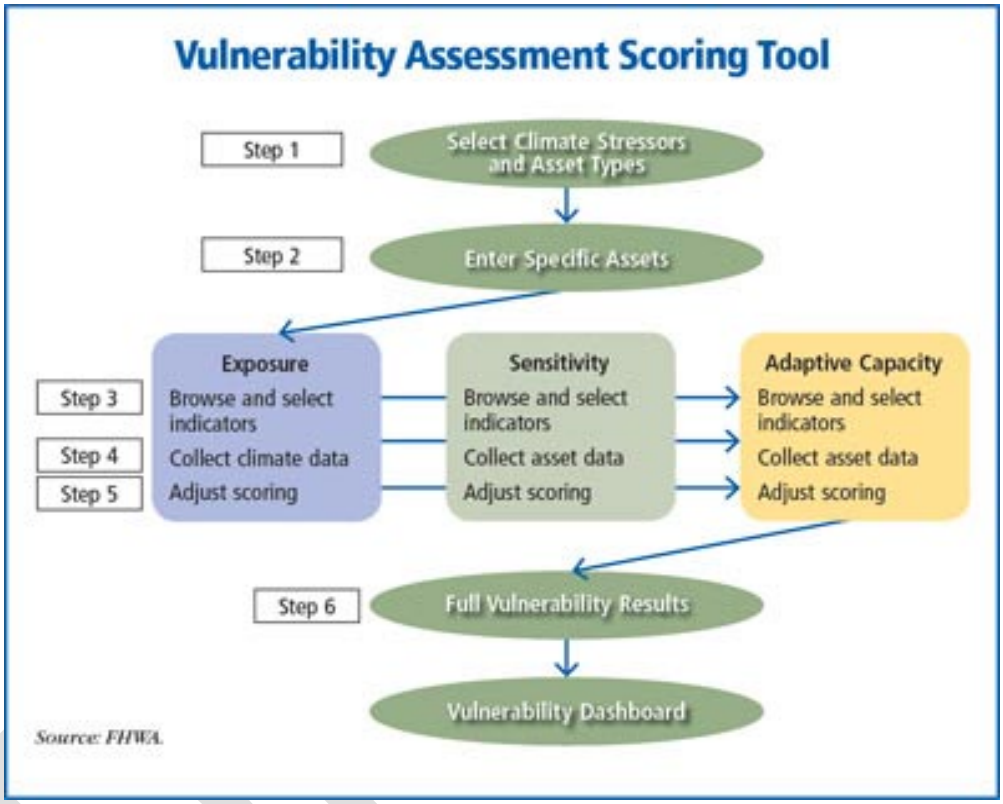


Figure 20. Flow chart depicting FHWA Vulnerability Assessment Scoring Tool. (Source: FHWA)

[77] The FHWA has developed a risk assessment pilot program entitled "Assessing Vulnerability and Risk of Climate change Effects on Transportation Infrastructure: Pilot of the Conceptual."
See: https://www.fhwa.dot.gov/environment/climate_change/adaptation/resilience_pilots/2010-2011_pilots/conceptual_model62410.cfm

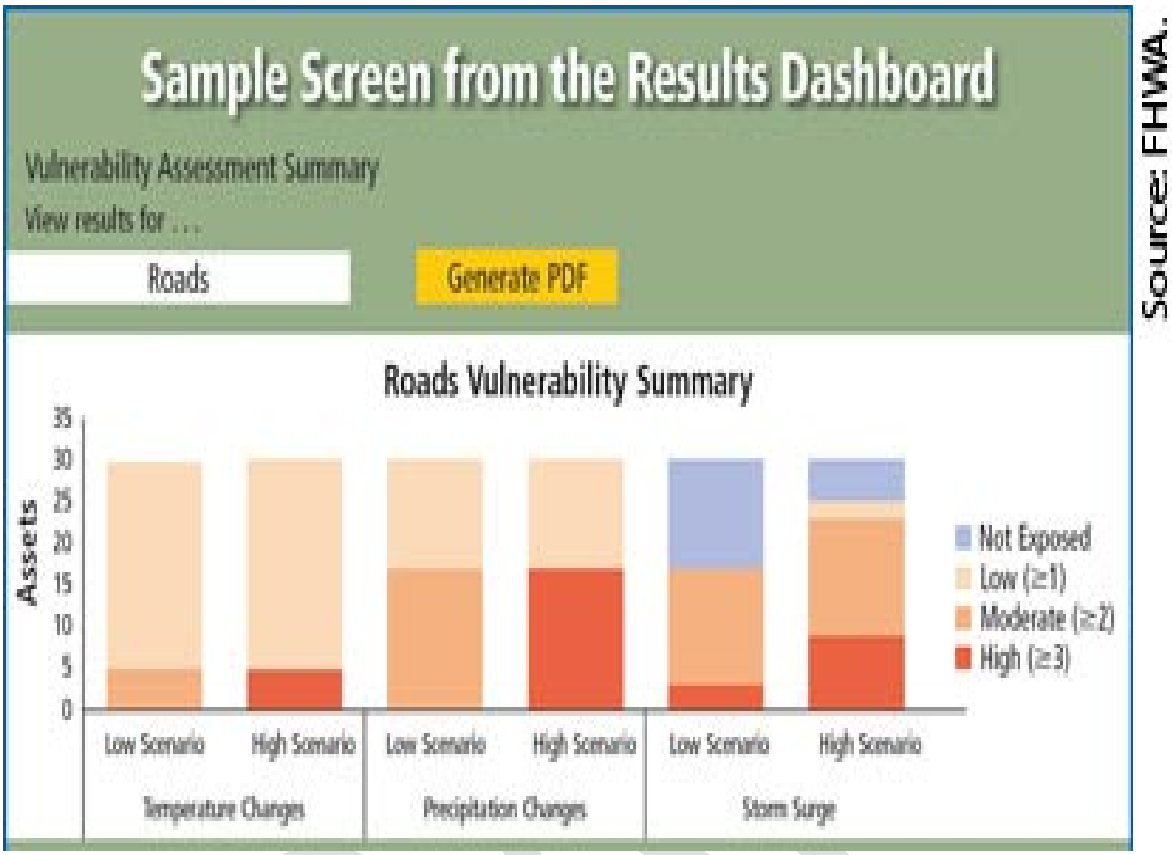


Figure 21. VAST dashboard. (Source: FHWA)

After hurricane Sandy, VAST was used to provide a framework for conducting Vulnerability Assessment by helping asset managers to choose stressors and assets to evaluate, develop and collect indicators, refine method to convert data to scores, and produce an output in the form a Vulnerability Scores for all assets.[78]

The Mobile, Alabama pilot developed used VAST as an asset-specific vulnerability model that identifies characteristics that serve as indicators of their sensitivity and adaptive capacity. The Pilot developed a methodology to compute a Vulnerability Score for each port based on the vulnerability formula, based on the following definitions:[79]

V = f (Exposure, Sensitivity, Adaptive Capacity);

The model produced the following "Port Storm Surge Sensitivity Indicators":

[78] The Coupled Model Inter-comparison Project (CMIP) is a United Nations tool developed as a standardized experimental protocol for studying the output of climate models. It incorporates data on sea-level rise and bridge sensitivity analysis, and engineering-based adaptation options for 10 transportation assets. Global Climate Models (GCMs) are part of CMIP Data Processing Tools, which can be downscaled to help high resolutions useful at the local level.

[79] FHWA; Mike Savonis, ICF International.

- Previous damage from storm;
- Shoreline protection
- Infrastructure elevation above sea-level;
- Asset age;
- Asset condition;
- Dependence on electrical power;
- Materials handled.

The model also produced the following "Port Adaptive Capacity Indicators":

- Ability to shift operations internally;
- Ability to shift ops externally;
- Estimated disruption duration for storm surge impacts.

The model identified the following Alabama facilities as most vulnerable:

- Highly exposed
- Demonstrated sensitivity in the past;
- Low-lying assets;
- Relatively inflexible operations;
- Reliance on electricity;
- Lack of redundancy.

Multi-Criteria Decision-Making

The fourth component of the risk assessment tools that FHWA developed for assessment of climate change risks was the tool with a specific focus on the HR climate stressors and risks. FHWA conducted the 2012 Hampton Roads Pilot for climate change vulnerability assessment conducted in collaboration with Virginia DOT and the University of Virginia.[80] The FHWA Pilot study developed a conceptual framework for incorporating ramifications of climate change in transportation planning—for both vulnerability assessment and risk assessment (RA).
A key component of the Hampton Roads climate change pilot is the Multi-criteria Decision Analysis (MCDA) model that was created as part of Haimes' impact assessment and risk-filtering framework. MCDA and the related scenario-based risk assessment tools are widely used to conduct an evaluation of environment and infrastructure system risks. MCDA allows vulnerable infrastructure assets to be prioritized based on a wide range of competing decision criteria. It allows complex decisions to be made under constraints of incomplete or unstructured data-availability. The tool enables RA to be performed with few modeling or computational

[80] *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot*. VDOT, UVa, HRPDC, FHWA. 2012.

resources relative to more complex alternatives. 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.[81]

The HR risk-assessment framework consisted of three interrelated and concurrent steps:

1. Develop an inventory of assets, and prioritize it based on vulnerabilities captured in climate change information;
2. Combine climate change data for the region with findings of the region's vulnerability assessment to understand the specific drivers of the vulnerabilities;
3. Conduct quantitative RA to identify the most vulnerable transportation assets, based on the framework provided by Haimes and Lambert[82] (as described above).

The FHWA HR Pilot was designed to:

- Explore interactions between climate change and other factors such as recession, government regulations, maintenance/repair needs, and ecological degradation;
- Establish connections between these combinations of science, and the transportation planning process; and
- Enable prioritization of limited resources so that optimal allocation and timely intervention is achieved.

Figure 22 depicts the analytical process used in the HR Pilot for risk assessment:

[81] For research on MCDA, see: Paul Kirshen, et al. "Simplified Method for Scenario-based risk assessment adaptation planning in the coastal zone." *Climate Change: An Interdisciplinary International Journal,* (2011). Gilberto Montibeller and A. Franco. "Multi-Criteria Decision Analysis for Strategic Decision Making." *Handbook of Multi-criteria Analysis Ch.2,* (2010).

[82] Haimes, et al. October 2004.

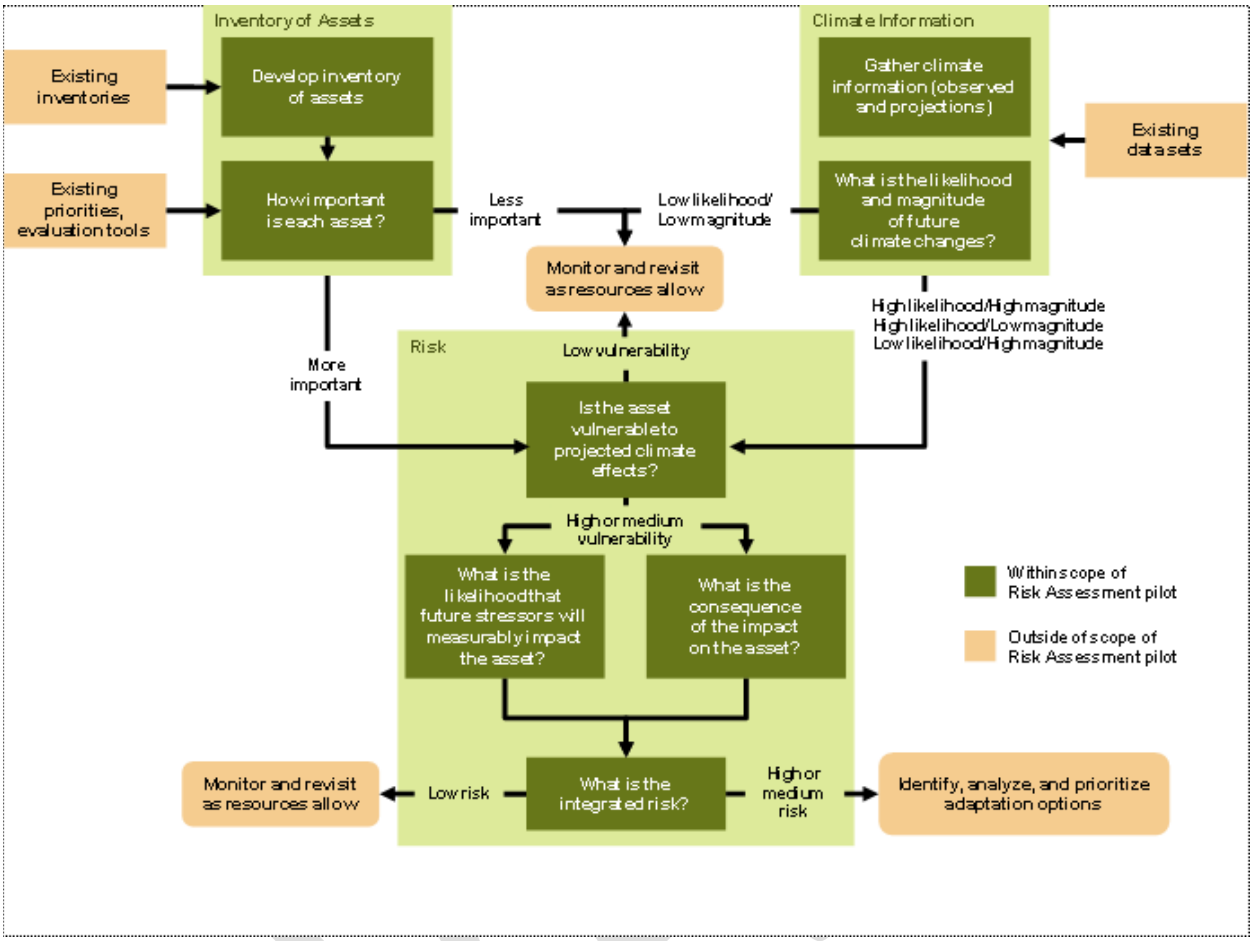


Figure 22. Structure of the FHWA conceptual framework for risk assessment and adaptation of transportation infrastructure to climate change. (Source: *Hampton Roads Virginia Pilot*, FHWA)

The pilot's scope, and the inventory of the existing transport assets were planned in accordance with the VDOT Asset Management System (AMS). The AMS database contains information on thousands of assets that include mobile and immobile assets (e.g., bridges, roads, tunnels and the Pontis database for condition of primary bridges).[83] Four screening criteria were used to reduce the scale of the problem to fewer than 20 major assets that:

a. Are hurricane evacuation routes;
b. Carry high traffic volumes (AADT >10,000 vehicles/day);
c. Represent a maintenance priority route (e.g., snow removal priority routes);
d. Are located at low-lying elevations.

[83] Pontis is a comprehensive bridge management system to assist agencies in allocating scarce resources to protect existing infrastructure investments, ensure safety, and maintain mobility. See Appendix C for a more detailed description.

In parallel with this effort, 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 measure the climate impacts and create new priorities across the four elements of assets, projects, Traffic Analysis Zones (TAZ) and policies.

The Pilot methodology was driven by the priorities and infrastructure projects underway within the region during the Pilot. The FHWA pilot report notes the key factors that drove the regional priories in three different directions, and significantly influenced the implementation of the Pilot:

- *Transportation Asset Condition Priorities*: This priority was set by VDOT based on the agencies key asset classes in its AMS. VDOT identified eight specific HR assets—bridges, roads, tunnels, highway sections, and several Traffic Control Centers (TCC)—that were derived primarily from the state's hurricane evacuation plan. The agency considered these assets key by the regional risk strategy. These four criteria were intended to focus the pilot demo on high-risk assets. It resulted in designation of three bridges and two Traffic Management Centers (TMCs):
    - Chesapeake Bay Bridge Tunnel
    - Berkeley Bridges
    - Gilmerton Bridge
    - Two TMCs
- *Network Access and Economic Opportunity Priorities.* This was the priority maintained by the HRTPO and HRPDC, driven by their proposed projects that were designed to emphasize the criticality of transportation assets that served the mobility of the region's population centers and promoted its underlying economic activities. The major transportation projects identified by these planning agencies included a list of 155 projects, planned over a 30-year horizon for the region's long-range transportation plan (LRTP). These projects were prioritized according to certain published criteria that formed the basis for a prioritization algorithm. The list was divided into highway, bridge, tunnel, and international trade transport operations. Various multimodal policies were included in the model to evaluate the effect of different policy frameworks. From these, a list of 21 statewide policies and 4 region-specific policies were chosen from the LRTP—subdivided into funding/investment; land-use; connectivity—MCDA priority-setting process was conducted based on the elements of climate risk/vulnerability data.

- *Innovating Risk Mitigation Priorities*. These priorities were maintained primarily by the UVA team, and reflected their research and development (R&D) interest in identifying innovative solutions and climate change tools that would serve the research priorities of the broader academic community.

The priority-setting component of the MCDA model was done in the context of four separate components for the FHWA HR pilot: Existing plans; Proposed LRTP and regional capital investment plan (CIP) projects; traffic analysis zone (TAZ) location; and multimodal policies at several government levels.[84] The importance of TAZ had to do with proximity to the coast, and the size and population density of the at-risk location. By separating these four elements, decision-making and prioritization would be more likely to be done effectively. The model also had climate change scenarios to incorporate the growing body of knowledge on climate change impacts (as outlined in Step 5 in table below). The HR framework for MCDA scenarios explored:

- Interactions between climate change and the economy, government expenditures, ecology, technology;
- Connections between these combinations of scenarios and transportation planning processes; and,
- Prioritization of limited resources to achieve optimal allocation.

The selection of scenarios allowed for non-climate conditions to also enter into the prioritization process (e.g., government expenditures, technology change for inspection and asset maintenance, population growth; energy shortage; change in land-use regulations). The framework was able to conduct vulnerability and risk assessments based on the MCDA data combined with scenarios in an MS Excel workbook that displays the scores of the projects across the scenarios and the baseline scores of each project, the results of which is a priority ranking of projects, as outlined in Table 17 below:

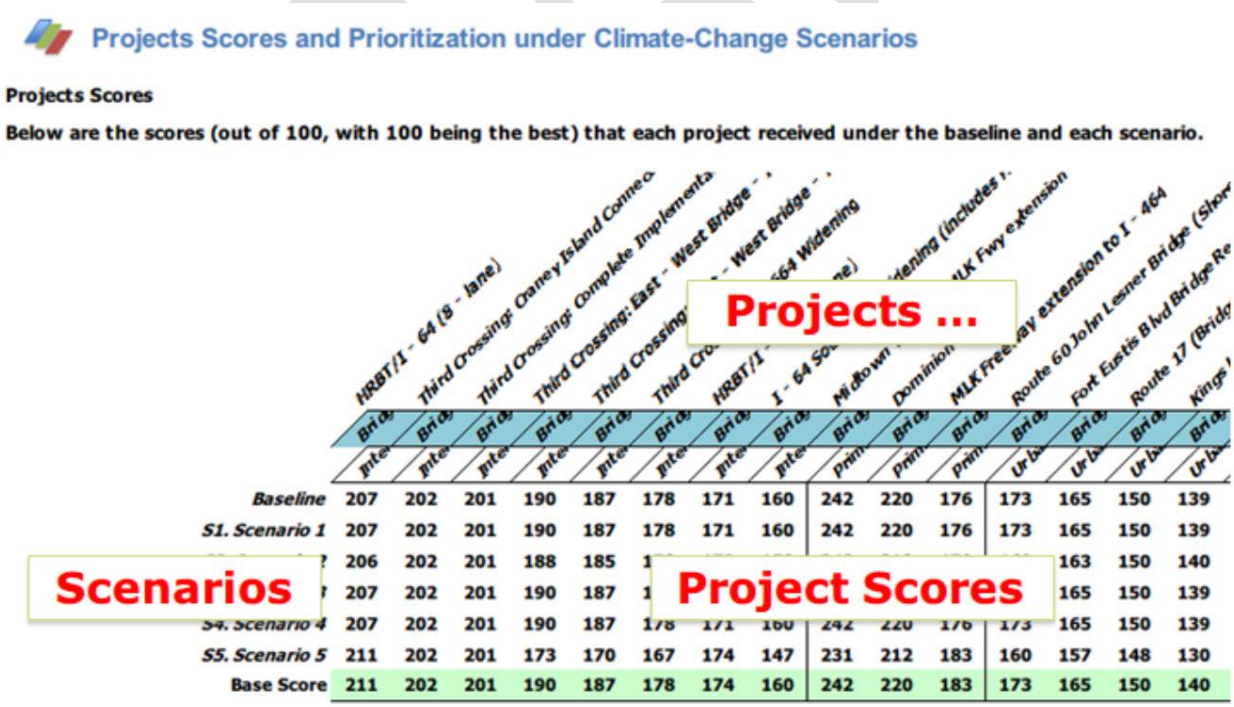
Table 17. MCDA assessment components and outputs. (Source: VDOT/Hampton Roads Pilot)

Steps	MCDA Assessment Components	Output
Step 1	Define the criteria and assign max score (relative importance) for each [e.g., for each asset (highway, bridge, rail, transit, airport) aligning criteria: congestion system condition, cost effectiveness ($/VMT) safety/security]	Assigned scores and measures of criticality
Step 2	Define the list of projects to be prioritized	Regional CIP or

[84] The pilot obtained climate information from 40 Traffic Analysis Zones (TAZ) that were identified as representative regions within the larger metropolitan area to demonstrate the impact of climate change. The TAZ' were randomly selected to represent the regional distribution of location, size and proximity to the coast.

		equivalent project lists
Step 3	Assign baseline ratings to projects defined in Step 2 according to criteria define in Step 1	Automatically generated ratings
Step 4	Calculate the aggregated score of each project via built-in MCA criteria value function based on inputs from Step 1-3	Baseline project ranking
Step 5	Develop up to 5 default climate and non-climate scenario-conditions: *Scenario 1*: Increase in SLR+ storm surge *Scenario 2*: SLR + Storm Surge + economic recession *Scenario 3*: SLR + Storm Surge + increased wear & tear on public infrastructure *Scenario 4*: SLR + Storm Surge + ecologic damage/species loss/infectious diseases *Scenario 5*: SLR + Storm Surge + increased traffic density + population +tourism growth	Conduct Scenario-based analysis based on the matrix of project scores and priorities in the corresponding check box (as in following matrix)

Figure 23 shows the matrix of the scores for each of the climate scenarios in the FHWA MCDA assessment for Hampton Roads. (Note that the chart is for illustration purpose, since the scores are not representatives of typical ranking scale of 0-100; all the scores are above 100).



Projects Scores and Prioritization under Climate-Change Scenarios

Projects Scores

Below are the scores (out of 100, with 100 being the best) that each project received under the baseline and each scenario.

Projects ...

Scenarios

Project Scores

	HRBT/I - 64 (8 - lane)	Third Crossing: Craney Island Connec	Third Crossing: Complete Implementa	Third Crossing: East - West Bridge	Third Crossing	Third Cro	HRBT/I	I - 64 So	Midtown	Dominion	MLK Free	Route 60 John Lesner Bridge (Show	Fort Eustis Blvd Bridge Re	Route 17 (Bridg	Kings
	Brid	Brid	Brid	Brid	Brid	Brid	Brid	Brid	Brid	Brid	Brid	Brid	Brid	Brid	Brid
	Inte	Inte	Inte	Inte	Inte	Inte	Inte	Inte	Prim	Prim	Prim	Urb	Urb	Urb	Urb
Baseline	207	202	201	190	187	178	171	160	242	220	176	173	165	150	139
S1. Scenario 1	207	202	201	190	187	178	171	160	242	220	176	173	165	150	139
[illegible]	206	202	201	188	185	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	163	150	140
[illegible]	207	202	201	190	187	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	165	150	139
S4. Scenario 4	207	202	201	190	187	178	171	160	242	220	176	173	165	150	139
S5. Scenario 5	211	202	201	173	170	167	174	147	231	212	183	160	157	148	130
Base Score	211	202	201	190	187	178	174	160	242	220	183	173	165	150	140

Figure 23. Matrix of the Scores for each of the climate scenarios in the FHWA MCDA assessment for Hampton Roads. (Source: VDOT/Hampton Roads Pilot)

EPA's Climate Impacts and Risk Analysis (CIRA) Tool

CIRA is a tool developed by EPA to analyze potential climate change impacts to four types of infrastructure in the U.S.: roads, bridges, urban drainage, and coastal property. For bridges, the CIRA model identifies inland bridges in the contiguous U.S. that may be vulnerable to increased peak river flows due to climate change, and estimates the costs of adaptation and mitigation for at-risk infrastructures. For roads, CIRA assesses the risks to roads associated with climate change. For a coastal property, CIRA estimates the costs that would be incurred due to climate change, with and without adaptation. For these estimates, CIRA relies on SLR projections through 2100 to account for dynamic ice-sheet melting based on semi-empirical climate model adjusted to regional land movements using local tide gauge data.[85]

NOAA's Climate Adaptation Tools: Coastal Resilience Index and Social Vulnerability Index

Coastal Resilience Index is an example of the tools that NOAA has developed, through its National Sea Grant Network, to assist coastal planners and R&R officials to plan for climate change. The goal of the Coastal Resilience Index is to provide a practical set of guidelines for communities to identify gaps, and examine the extent of their preparedness. In a related initiative, in compliance with the Presidential Policy Directive 8 (PPD-8) requirements for nation preparedness, NOAA is working with FEMA to develop the National Disaster Recovery Framework (NDRF) to be implemented at the regional level. At the community level the NDRF, along with tools such as Coastal Resilience Index, engage in a process that NOAA officials have referred to as "Precovery Planning," i.e., a process that guides the regional R&R managers to take into consideration, at each stage of planning for the next coastal storm event, the operational factors that proved consequential in the past.

NOAA has also developed a tool that serves as a measure of a region's Social Vulnerability Index (SoVI). NOAA designed the tool to measure the adverse consequence of recurrent flooding on the exposed populations. SOVI computes 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 (see Section 4-4 on Social Vulnerabilities).

NASA's Climate Adaptation Science Investigator (CASI) Tool

NASA has developed the *Climate Adaptation Science Investigator* (CASI) as a tool for center-specific climate change impacts and adaptation. The tool was launched in 2010 for developing adaptation measures for NASA's five East Coast centers, including the Langley Air Force Base and Wallops Flight Facility in Virginia, to address the risks of SLR, hurricanes, flooding, and land

[85] *Climate Change in the United States: Benefits of Global Action.* EPA, 2015.

subsidence. The primary tasks of the CASI team were to: (a) downscale center-specific hazards and data; (b) conduct R&D customized to the centers; (c) build inventories of activities; and (d) implement adaptation measures. The CASI Team has developed projections for planning horizons 2020, 2050, and 2080, with projections of average precipitation, SLR, and SLR under a rapid ice-melt scenario.[86]

The broad array of methodologies, processes, and tools documented in this section point to not only to the wealth of techniques available to assess the economic costs of climate change, but also lack of consensus among decision makers about how to address and prepared for climate change risk. These challenges are further discussed in Sections 5 and 6.

4 – Preliminary Estimates of the Costs and Exposure Levels of Norfolk/HR Region Transportation Infrastructure

This section reviews baseline information from damage data available from several sources, including HAZUS-MH, SHELDUS, NOAA, and HRPDC.

4-1 Historical Damage Data for Floods and Hurricanes

There are two major sources of historical damage data available for HR and Norfolk from SHELDUS and NOAA.

SHELDUS Data

Spatial Hazard Events and Losses Database for the U.S., or SHELDUS, as described in Appendix C- Data Sources, is a database of county-level property damage for losses attributed to flooding and storms-related events for years 1960-2014. Table 18 and Figure 24 depict SHELDUS data for property damage incurred in Norfolk, VA over that 54-year period. The chart shows the dollar value of the damages incurred in Norfolk as a consequence of five storm-related hazards: coastal surge not associated with a hurricane ($29M); flooding not associated with a hurricane ($34M); hurricane/tropical storm ($45M), other severe storms ($5M); and wind ($4M), with a 54-year total of $116M. Data on the dates of most severe damage, shown in Figure 24, suggest that most of the historic property damage over this 54-year period have been due to a handful of relatively infrequent events of large magnitude. In the case of floods not associated with a hurricane, almost all of the damage resulted from two single flood events that occurred in 1969 and 1998. In the case of hurricanes/tropical storms, most of the damage was from four storms

[86] *Climate Risk Management Plan: Managing Climate Risks and Adaptation to a Changing Climate*. NASA, 2014. Rosenzweig, et al. "NASA's CASI: Building Climate Resilient NASA Center." *Livebetter Magazine,* (Dec. 2011).

that all occurred within the past 20 years. Similarly, four coastal surge events are responsible for most of the damage from this hazard type.

Table 18. SHELDUS data on estimated damages for major hazards in Norfolk. (Source: SHELDUS)

Hazard type	Total estimated property damages in Norfolk (1960-2014) in 2014 dollars
Hurricane/tropical storm	$45 million
Flood (not associated with hurricane or coastal surge)	$33 million
Coastal surge (not associated with hurricane)	$29 million
Other severe storm	$5 million
Wind	$4 million
Total	$116 million

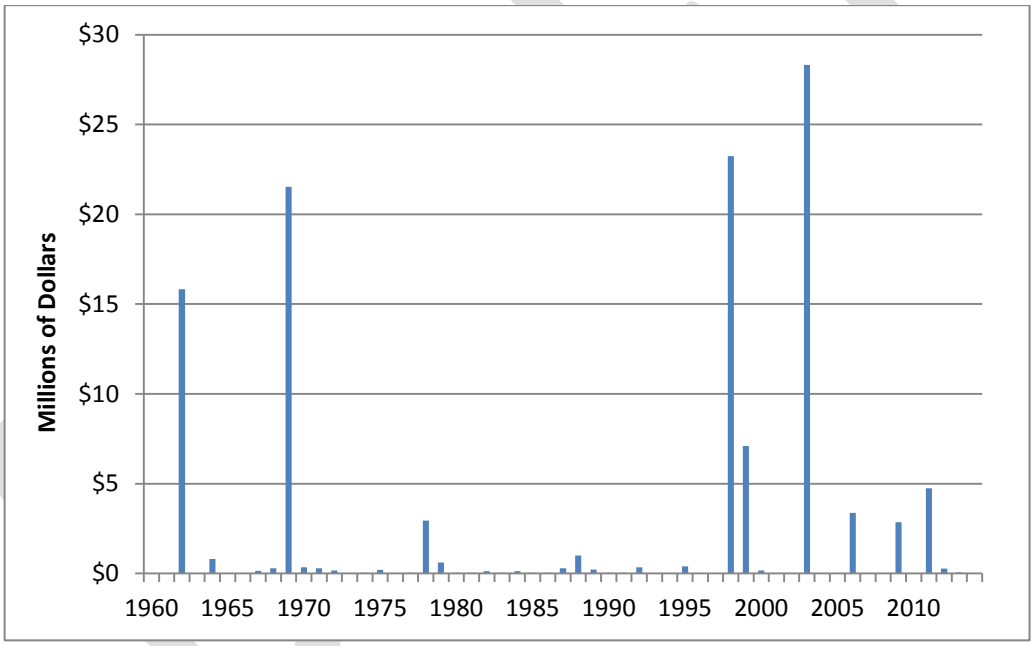


Figure 24. SHELDUS data on total annual estimated property damages in Norfolk from coastal surges, floods, winds, hurricanes, and other severe storms (1960-2014). (Source: SHELDUS)

NOAA Storm Event Database of Losses

NOAA's Storm Event Database[87] has data on storm events impacting Norfolk, VA. Figure 25 shows data for 1957 through 2012, but data on hurricanes and floods are only available from 1997 to 2012. The data prior to 1997 include the following event types: lightning, high wind, tornadoes, and hail.

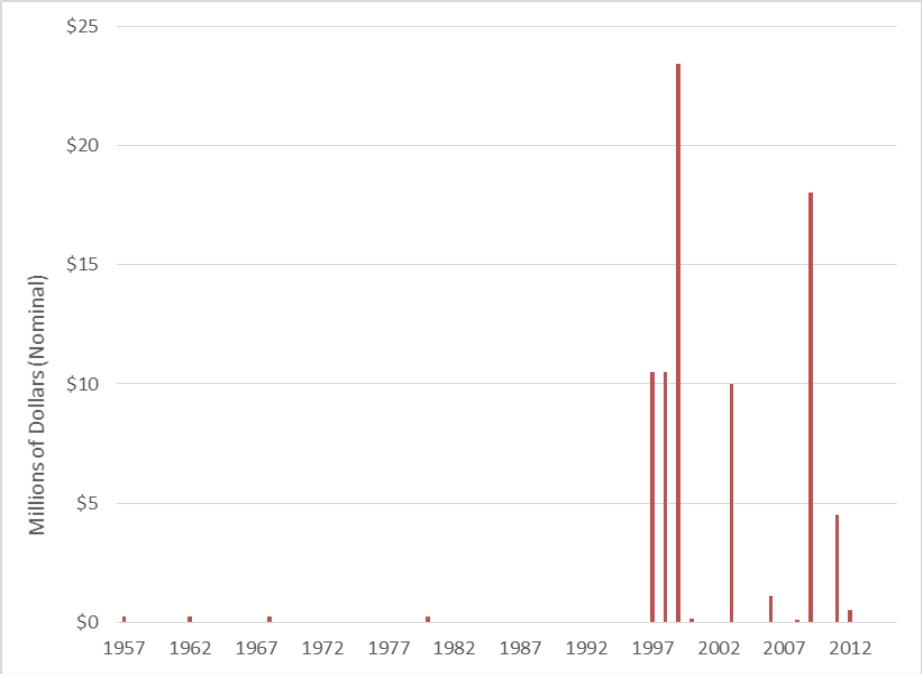


Figure 25. NOAA data on estimated property damage from storm events in Norfolk.
(Source: NOAA Storm Events Database)

4-2 Determining Transportation Asset Value: Data on Potential Scale of Infrastructure Damage Costs

HRPDC Infrastructure and Property Loss Damage Estimates

The HRPDC Phase III study of SLR risks in HR has produced an extensive report on the exposure of the HR jurisdictions and their transportation network to SLR risks, and has developed baseline data on the potential economic losses in the region from future extreme weather events.[88] Appendix C describes the methodology HRPDC used to estimates the 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

[87] "Storm Events Database." NOAA. See: https://www.ncdc.noaa.gov/stormevents
[88] *Climate Change in Hampton Roads: Phase III: Sea Level Rise in Hampton Roads, VA.* HRPDC, July 2012.

inventory of properties that would be significantly impacted by 1-meter of SLR, under all three risk scenarios for exposure—low, middle, and high—to one meter SLR above spring high tide.

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. Comparing the SHELDUS records of property damage of $116M from the flooding events in Norfolk for the 1960-2014 period with the HRPDC Phase III vulnerability study revealed some stark contrasts, as examined in the following section. The HRPDC 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. 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 19 and Table 20 below show the summary exposure risk data for the HR region and for the City of Norfolk, respectively.

Table 19. Exposure to one meter SLR above spring high tide in Hampton Roads. (Source: HRPDC Phase III Report)

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	$30,833,003,959
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

Table 20. Exposure to one meter SLR above spring high tide in Norfolk. (Source: HRPDC Phase III Report)

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 21 below summarizes the monetized values, derived from Tables 19 and 20 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 of SLR risks (based on the risk scenarios for Exposure to One Meter SLR above Spring High Tide.)[89] The table underscores the greater vulnerability of Norfolk compared to the HR region as a whole: Norfolk faces the potential loss of approximately 10% of its assets (value between $1.3B and $2.2B) compared to the regional exposure levels of about 7% of the properties.

Table 21. Potential asset loss for Norfolk and HR properties from exposure to SLR risks. (Source: HRPDC Phase III Report)

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%)

[89] 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).

Sandia's Estimates of Direct and Indirect Economic Impacts of Flooding Risks in Norfolk

Sandia National Laboratories has developed the Regional Economic Accounting (REAcct) Tool as a flexible, easy-to-use estimating model for estimating the economic impacts of disruptions due to climate-related disruptions. REAcct is an I-O model that provides regional or county-level estimates of direct and indirect impacts of the firms whose business has been adversely impacted by the disruption. The tool has a GIS-based estimating capability that calculates the number of employees directly impacted by the event, while relying on the RIMS II Input-Output multipliers to incorporate the indirect impacts on the region's firms.[90]

The Sandia research team ran the REAcct tool to estimate the potential economic impacts of the City of Norfolk's exposure to the risks of flooding and climate change. Figure 26 shows Sandia's 2015 estimates of direct losses to top 5 industries in Norfolk as a consequence of a 4-day business disruption for three exposure scenarios for SLR and flood: Scenario 1: 100 year flood; Scenario 2: 100-year flood + 1.5ft; Scenario 3: 100yr flood + 3 ft. In the Professional/ Technical sector, for instance, Norfolk's direct losses would range between $32M and $60M, from a 4-day business disruption, depending on the storm intensity scenario.

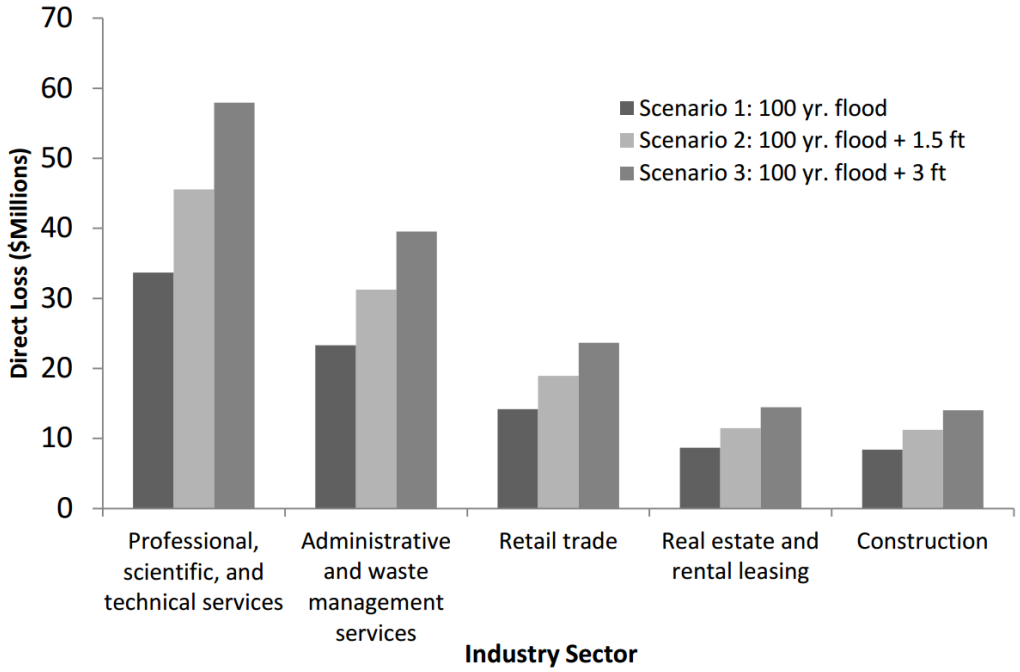


Figure 26. Top 5 direct losses in Norfolk, as a consequence of a four day business interruption under three exposure scenarios. (Source: Sandia National Lab, 2011)

[90] *Regional Economic Accounting (REAcct): A Software Tool for Rapidly Approximating Economic Impacts*. Sandia National Laboratories, July 2011.

Sandia computed the total potential losses in Norfolk, direct and indirect, from a 4-day disruption. The model showed the potential direct losses for Norfolk, to range between $27M and $56M, depending on storm severity scenario as a consequence of a 4-day disruption. 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, to range between $70M and $144.6 M for the 4-day storm-related damages, as summarized in Table 22.

Table 22. Estimates of direct and indirect losses in Norfolk for a four day business interruption under three scenarios. (Source: *REAcct Report*, Sandia National Lab)

	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

Figure 27 below compares the magnitude of direct losses in Norfolk with those for four other HR cities.

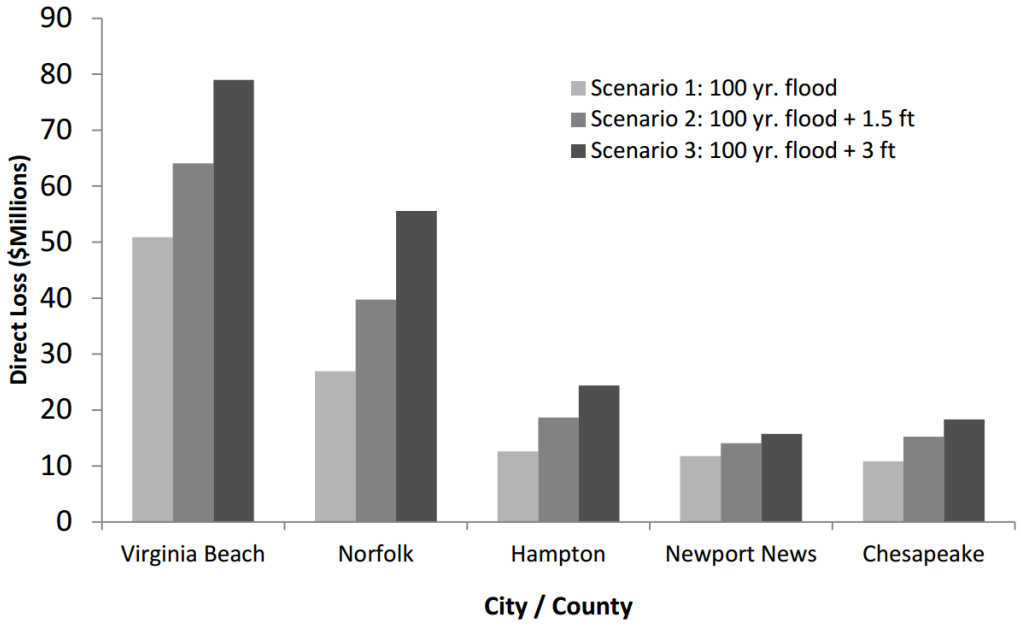


Figure 27. Top five HR cities ranked by direct losses due to four days of disruption. (Source: Sandia National Lab, 2011)

Sandia's study of climate risks in HR also include estimates of risks to power generation facilities. The study identified 19 electricity generation substations in HR, and 5 in Norfolk, that were potentially exposed to flooding risks. Figure 28 shows the locations of electric power facilities in HR at potential risk of exposure to SLR.

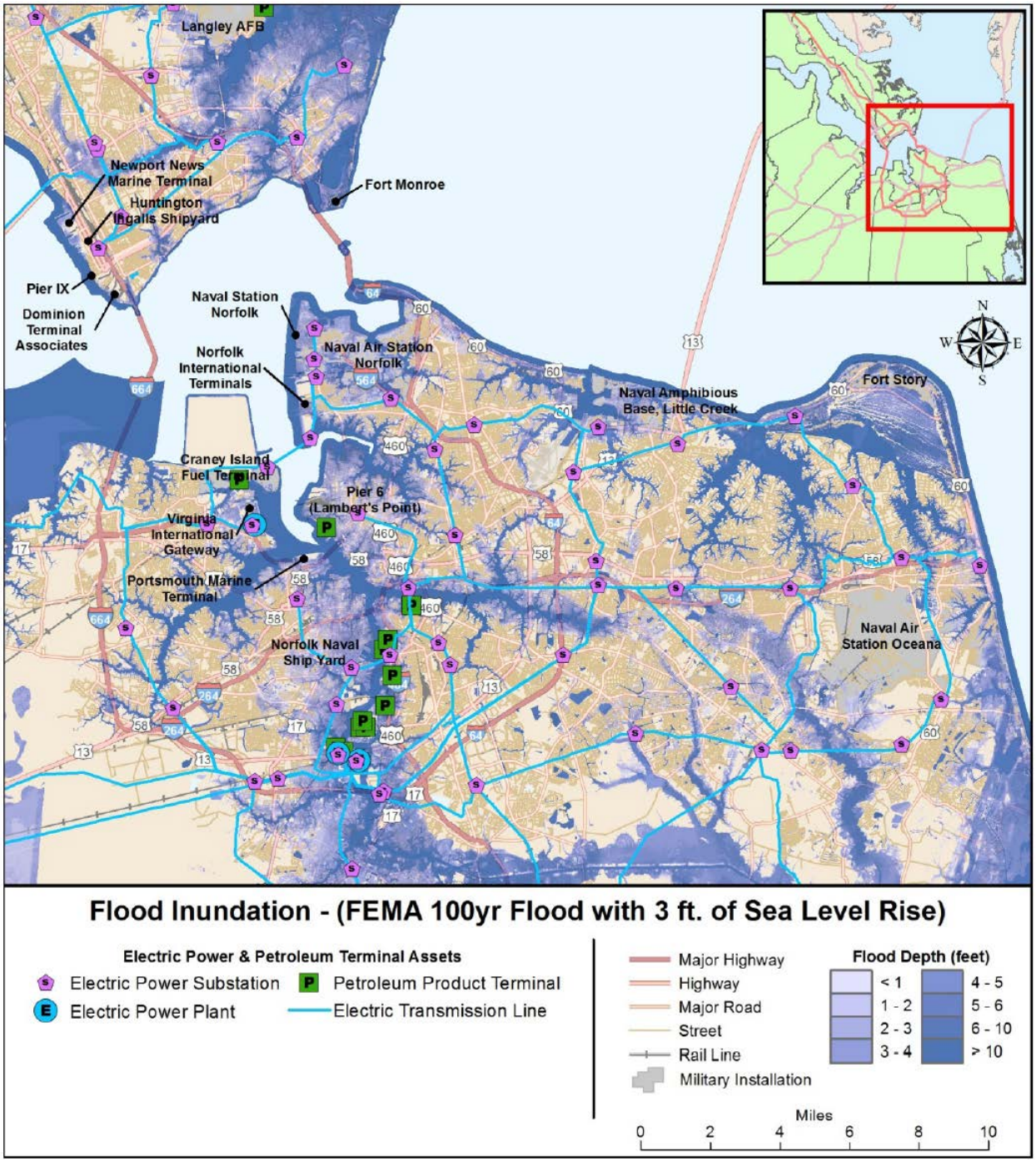


Figure 28. Power stations in HR and Norfolk at risk of flooding. (Source: Sandia National Lab, 2011)

The significance of the Sandia estimates, using its REAcct input-output (I-O) model, is further discussed below in section 4-3 in the context of estimating the impacts of climate disruption in transportation.

4-3 Quantifying the Economic Impacts of SLR on the HR Military and Transportation Sectors

This section documents the findings of several studies conducted to quantify the full economic impacts of three key employment sectors in HR—the defense industry, aviation, and marine container ports—with particular emphasis on the Norfolk area.

Economic Impacts of the Military Sector

The military facilities located in HR and Norfolk are highly vulnerable to flooding and SLR threats. Langley Air Force Base, for instance was flooded in 2003 by a 5.5' storm surge in the aftermath of Hurricane Isabel. The Base facilities were inundated by two feet of storm water, resulting in a week-long closure of the facilities.[91]

A 2013 study by HRPDC on the economic impacts of defense installations in the region provides information on the scale and type of military employment and expenditure in HR and Norfolk.[92] Table 23 lists employment data for five of the key DOD facilities in or around Norfolk, reporting a total of over 63,000 Active Duty personnel, over 9,000 Reserves, and over 32,000 civilian employees, amounting to a total direct employment of 104,563.

Table 23. Norfolk Area Military Facilities. (Source: Economic Impacts of the DoD in Hampton Roads, HRPDC, 2013)

Norfolk Area Military Facilities	Active Duty	Reserves	Civilian
Norfolk Naval Base	37,223	2,982	13,667
Joint Base Langley-Eustis	12,599	2,833	5,627
Joint Base Little Creek-Fort Story	9,676	2,593	2,154
Dam Neck Training Center Atlantic	3,580	851	1,091
Norfolk Naval Shipyard*	1	41	9,645
Total Norfolk Area Facilities (Grand total of all three categories = 104,563)	63,079	9,300	32,184

* Norfolk Naval Shipyard is actually located in Portsmouth.

In addition to describing the military facilities, their functions and employment levels, the HRPDC study also conducted an Economic Impact Study to quantify the direct and indirect economic impacts of DOD employment in HR. The study team used the REMI Input-Output

[91] *Making Space for the Future*. NASA Langley Research Center, 2006.
In 2006, Langley had the following spending profile: 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).
[92] *Economic Impacts of the Department of Defense in Hampton Roads.* HRPDC, Oct. 2013.

model and CGE methodology to estimate the full economic impacts, direct and indirect employment impacts and contribution to the HR region's earnings and GDP, as summarized in Table 24 (see Appendix D for model for description of REMI model and other I-O and Computable General Equilibrium (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 employment in HR, 873 indirect and induced jobs are created inside and outside the region.

Table 24. Economic Impact of Military Personnel in Hampton Roads. (Source: Economic Impacts of the DoD in Hampton Roads, 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).[93]

The HRPDC report evaluated the extent of the military influence on the economy of HR in the context of three key trends in defense expenditures:

- A steady decline in the relative share of GDP from defense spending (from 43% of the nation's GDP in 1941, to 10% in 1968, and about 5% in 2010);
- Greater reliance on contracting, a practice that spreads the expenditure benefits to outside the region and reduces the volume of local employment: Between 1987 and 2010, the value of defense contracting (measured by the 5-year moving average of contract value) grew by more than threefold, from about $2.5 billion in 1987 to $8.5 billion in 2010, and;
- HR-specific impacts relating to shifts in defense strategies include three key strategic changes: the *Pivot to the Pacific;* changes in the Navy *home-port* practices; and the naval strategy shifts towards reduced number of aircraft carriers, with a greater reliance on "*Forward Basing*" of ships in in Rota, Spain to gain greater access to and more rapid response to the Mediterranean events. This strategy has resulted in relocating three of

[93] NASA/Langley, 2006.

the Naval Station Norfolk carriers vessels—an Arleigh-Burke-class destroyers, the Porter, and the Carney—to Rota. The implications of the DOD shift in homeport strategies have also been addressed in the ODU 2015 State of the Commonwealth Report.[94]

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 also been examined in Sandia's study of the economic impacts of SLR in Norfolk stresses (as reviewed in Section 4-2). The Sandia study underscored the extent to which the City of 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's) container shipping operations:

> *Norfolk operates as a cog among the HR's port machine. Therefore, protecting Norfolk from flooding will protect almost half of HR's coal shipping capability, and all of its container shipping capacity through NIT. Norfolk is innately intertwined with successful operations at NAVSTA Norfolk. The city's flooding resilience will have an impact on individuals working at several of these facilities, as well as the facilities themselves.*[95]

To determine the most beneficial adaptation options for the Norfolk Naval Station, USACE's Dr. Kelly Burkes (as described in Section 3-4) developed a 3-tiered risk assessment framework that involved a three-step decision process: site-selection, regional-assessment, and installation-specific assessment. The identified risks included several SLR and Storm surge scenarios: 0, 0.5, 1.0, 1.5, and 2.0 meter.[96] Table 25 shows the final scores for the five military sites in HR, considering the facilities scores with respect to the priorities dictated by each specific site, and the regional and installation-specific attributes.

Table 25. USACE SLR Adaptation Project Prioritization Scores for the Five Military Installations in HR. (Source: Dr. Kelly Burkes, USACE, 2014)

Military Installation	Location	Prioritization Score
Dam Neck Naval Combat Training Center	Virginia Beach, VA	14
Naval Station Norfolk	Norfolk, VA	12
Yorktown Naval Weapon Station	Yorktown, VA	11
Fort Eustis	Newport News, VA	11
Norfolk Naval Shipyard	Portsmouth, VA	8

[94] ODU, *State of the Commonwealth*, 2015.
[95] *Development of an Urban Resilience Analysis Framework with Application to Norfolk, VA*. Sandia National Lab, March 2016.
[96] Burkes-Copes, K. et al. USACE, Oct. 2014.

As for the role of the region's transportation network on the military facilities' exposure to risk, the HRPDC 2034 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.[97] These six Norfolk-area military facility capacity problem areas were:

- 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.[98]

As the section on EIA above has described, 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. The following sections review other studies that have estimated the regional economic impacts of aviation and marine container operations.

Aviation: Climate Risks and Economic Impacts

Location of Norfolk ORF airport has made it particularly vulnerable to SLR and storm surge. The census blocks in Norfolk, Portsmouth, and Newport News have shown the highest level of exposure to storm surge disruption according to the SLOSH model. A study conducted in 2011 for the Virginia Department of Aviation by ICF on the economic performance of the nine Virginia commercial airports estimated the total economic impact of aviation for the commonwealth at $20B. The report showed Norfolk's ORF to have total statewide economic impact of approximately $1B. The study on the regional airports also emphasized the region's susceptibility to climate events.[99]

[97] 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. Particularly as 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.

[98] *2034 Long Range Transportation Plan (LRTP), Section 4 – Transport Challenges, Military Capacity Needs.* HRTPO, Jan. 2012.

[99] *Virginia Airport System Economic Impact Study: Technical Report.* ICF International, prepared for Virginia Department of Aviation, Aug. 2011.

Another study conducted in 2004 estimated the ORF's total economic impact—direct, indirect, and induced impacts—at $1.4 billion.[100] 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:

- *Direct economic impacts:* accounted for roughly $178M (10%) of the economic impact, generated from passenger and cargo airline revenues, airport services and purchases; [101]

- *Indirect economic impacts:* accounted for roughly $567M (42%) 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% 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.

Seaports: Regional Economic Impacts

According to a recent report on the economic impacts of POV,[102] 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: Table 1 – Raymond A. Mason School of Business, William & Mary, *The Fiscal Year 2013 VA Economic Impacts of Port of Virginia*, December 26, 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

[100] *Economic Impact Study – 2004, Norfolk International Airport*. Jacobs Consultancy, prepared for Norfolk Airport Authority, Oct. 2007.
[101] 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.
[102] *The Fiscal Year 2013 VA Economic Impacts of Port of Virginia*, Raymond A. Mason School of Business, William & Mary, Dec. 2014.

Freight Service Support	$435	$189	$186	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: Table 2 – *Mason School of Business* report, Dec. 2014)

Components of POV Port Operations Impacts	Direct ($M)	Indirect ($M)	Induced ($M)	Total ($M)
Revenues/Sales	$2,434	$1,041	$1,721	$5,226
Value Added (GSP)	$1,113	$645	$1,087	$2,846
Employee Compensation	$862	$481	$589	$1,931
Total	$4,409	$2,167	$3,397	$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 $87.7B, or 19.5% of the Commonwealth's $448.8B GSP, partly due to the high percentage of the region-wide economic impacts of the port that is generated in HR.[103] Similarly, HR's total employee compensation of $49.3B was calculated at 19.1% of the VA total GSP.

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 value of $3.2 B. All these tonnage and cargo values accounted for about 29% 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% of the Virginia-used tonnage, and 25.3% of its value.[104]

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.

[103] The sources of data for the POV report were data from the BEA sectoral output that were used to calculate the total contribution of the HR MSA and POV to the regional economy.

[104] 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.

Table 28. Economic impacts of port trade in HR, by economic activity and impact type. (Source: Table 2 - *Mason School of Business* report, Dec. 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 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 from the 2000 HAZUS-MH data. This suggests that new port facilities were 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.

4-4 Quantifying the Full Costs of SLR and Flooding: Costs of Business Interruption, Loss-of-Use, and Loss-of-Income

Full costs of severe climate disruption events include not only the costs of direct damages—property losses, traffic disruptions, and destroyed transportation assets—but also indirect losses due to business interruption and loss of earnings, loss of insurance protection due to frequency of disruption, and amplified effects of poverty. NOAA has attempted to measure the latter effects by developing a "social vulnerability Index" to measure a community's ability to deal with poverty 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.

In Norfolk, there are three key correlates of vulnerability to flooding risks that have made 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.

The Indirect Cost Burden of Repetitive Losses and Uncompensated Damages

Recurrent flooding has been a major problem in Norfolk. NOAA has developed risk metrics that measure not only the standard *severity* of the climate events, but also their *frequency* as a significant risk factor. According to NOAA experts, these frequent disruptions, referred to as "*nuisance flooding*", is often a better indicator for predicting scale of future disruptions and measuring their impacts.[105] *Nuisance flooding* is defined as low-magnitude/high probability events that, according to NOAA projections, are "certain to increase dramatically with rising sea levels." These events are likely to have the greatest cumulative impacts on built environment and social/ecological systems over the coming decades. Regional risk analysts, including ODU's risk assessment experts on SLR risks, have emphasized that "nuisance flooding now happens on a monthly basis," a recognition that has become an essential part of the region's SLR preparedness and planning. NOAA has begun to develop data sources to complement the conventional NOAA models for measuring SLR and Storm Surge risk.

A major consequence of recurrent flooding is that many damages remain unpaid, which in turn makes it harder to quantify the cost burden of climate events, and determine the full extent of the needed adaptation measures. In 2009, the City of Norfolk had 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.[106] The FEMA HMA funds have not kept pace with the increased rate of flood damage. The HMA mitigation 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, have historically been

[105] Jeff Payne, Office of Coastal Management, NOAA. Testimony to the House Committee on Homeland Security, November 21, 2014.

[106] The FEMA HMA grant program covers installation costs of flood vents, elevating utilities, elevating structures, and outright purchase of property.

used to pay for these damages. Table 29 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.[107]

Table 29. 2013-2014 property loss data on repetitive loss properties. (Source: Wetlands Watch, undated)

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.

Norfolk's Poverty Rate: Influence of Social Vulnerabilities

HR has the largest percentage of residents in Virginia with incomes below the federal poverty level.[108] The HR poverty rate is 12.4%, compared to the rate of 6.8% in Northern Virginia, and the overall VA rate of 11.5%.[109] In Norfolk the median household income is about $44,747, compared to $62,666 for the Commonwealth as a whole (See Section 1-2 of this report on HR income levels and economic growth.)

Another metric for identifying the risks posed by poverty and income inequality is a region's Gini Coefficient. 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 exposure to climate risks. The Gini Coefficient is calculated with a value between 0 and 1, with 0 indicating absolute equality of income, and 1 indicating total inequality; equivalent of a single person capturing all income benefits. Norfolk's Gini coefficient is 0.469, higher than the Virginia Commonwealth rate pf 0.4301, and the US rate of 0.4603.[110] Norfolk's demographic profile suggests similar indications of the city's below-average economic status. A 2013 report

[107] Wetlands Watch, (undated); 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.
[108] *HR Vision – Annual Report*. HR Partnership, Sept. 2013.
[109] The *HR Vision* reports that in 2011, HR had a per-capita income of $11,484 for an individual.
[110] 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.

conducted for NOAA on climate change exposure risks by Rutgers University researchers characterized Norfolk's vulnerabilities through this profile:

> *Norfolk had a lower than average percentage of owner-occupied homes (39.6%); a lower than state average median household income ($37,546); a lower than average per-capita income ($23,471); a higher population density (4,571 people per square mile); and a relatively low population and job growth rate.* [111]

NOAA, having recognized the adverse impacts of recurrent flooding on the exposed populations, has developed a Social Vulnerability Index (SoVI) designed as a measure of region's vulnerability to natural hazards. The tool analyzes the census-block, or census-tract-level, data on incomes and poverty rates to identify the vulnerabilities of poor and disadvantaged communities to climate disruptions.

EPA has also recognized the value NOAA's SoVI, and has begun using the tool to quantify social vulnerability to natural hazards as part of the EPA Climate Change Impact and Risk Analysis (CIRA) tool. CIRA builds on the output of its coastal property impact-assessment to examine the "environmental justice" implications of projected SLR and storm surges in a community, quantify how the impacts are distributed across different socioeconomic populations along the coastline, and how they are likely to pay for the adaptation costs and the recurrent damages.[112] A 2015 EPA report has maintained that the vulnerability estimates of SoVI, together with CIRA's "environmental justices" components, are well-vetted impact assessment tools that statistically control for the influence of environmental and climate risk factors. As such, these tools serve as effective impact- assessment tools that eliminate the errors of double-counting climate risks when combining socioeconomic data with SLR and storm-surge data. As shown in the figures that follow, the social vulnerability index for Norfolk suggests that the most vulnerable populations are primarily in the southern part of the city.

[111] Judd Schechtman and Michael Brady. *Cost Efficient Climate Change Adaptation in the North Atlantic*. Rutgers University, in support of NOAA, 2013.
[112] *Climate Change in the United States: Benefits of Global Action*. EPA, 2015.

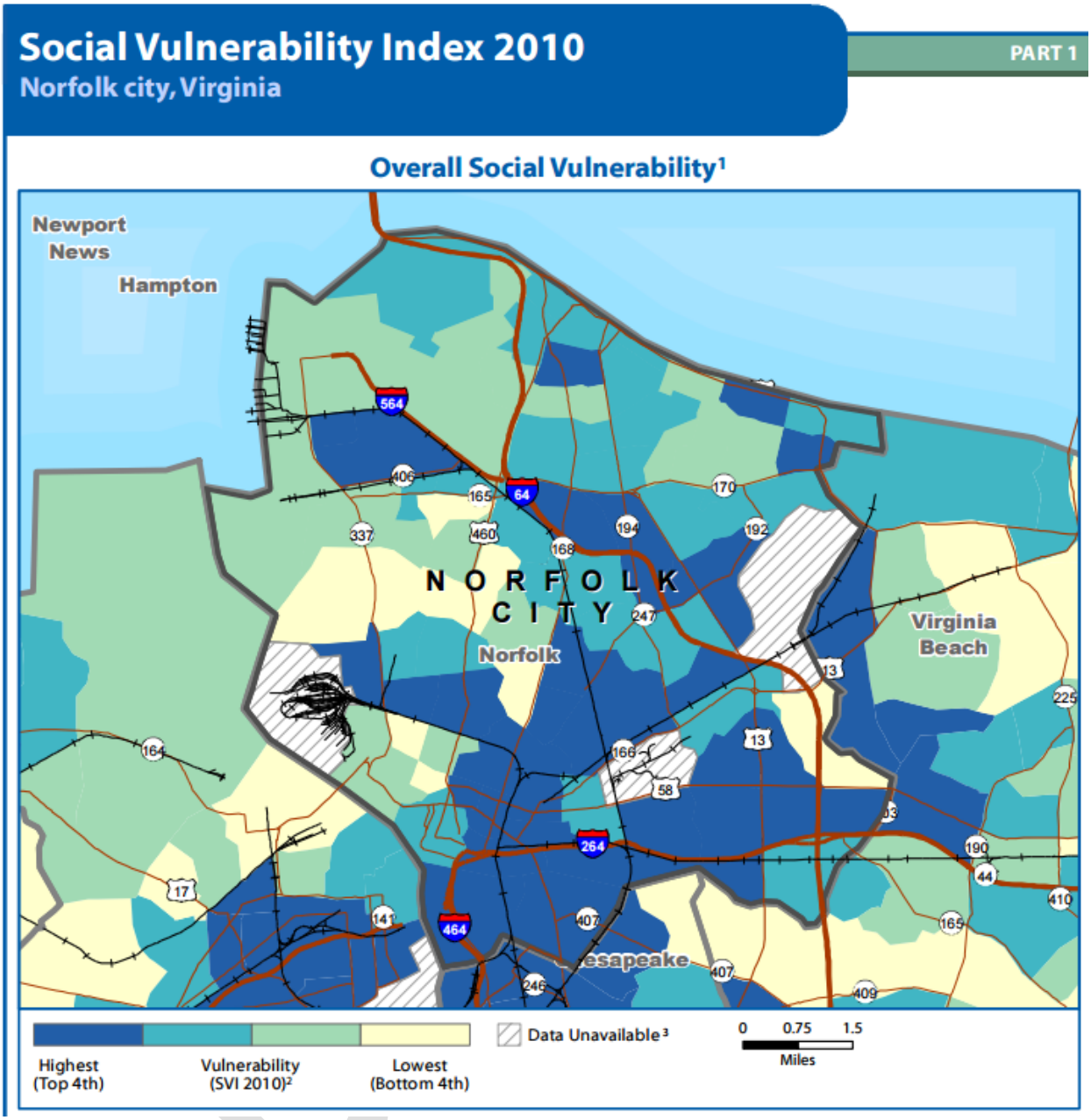


Figure 29. Social Vulnerability Index for Norfolk, Virginia (Source: http://svi.cdc.gov/PreparedCountyMaps.html)

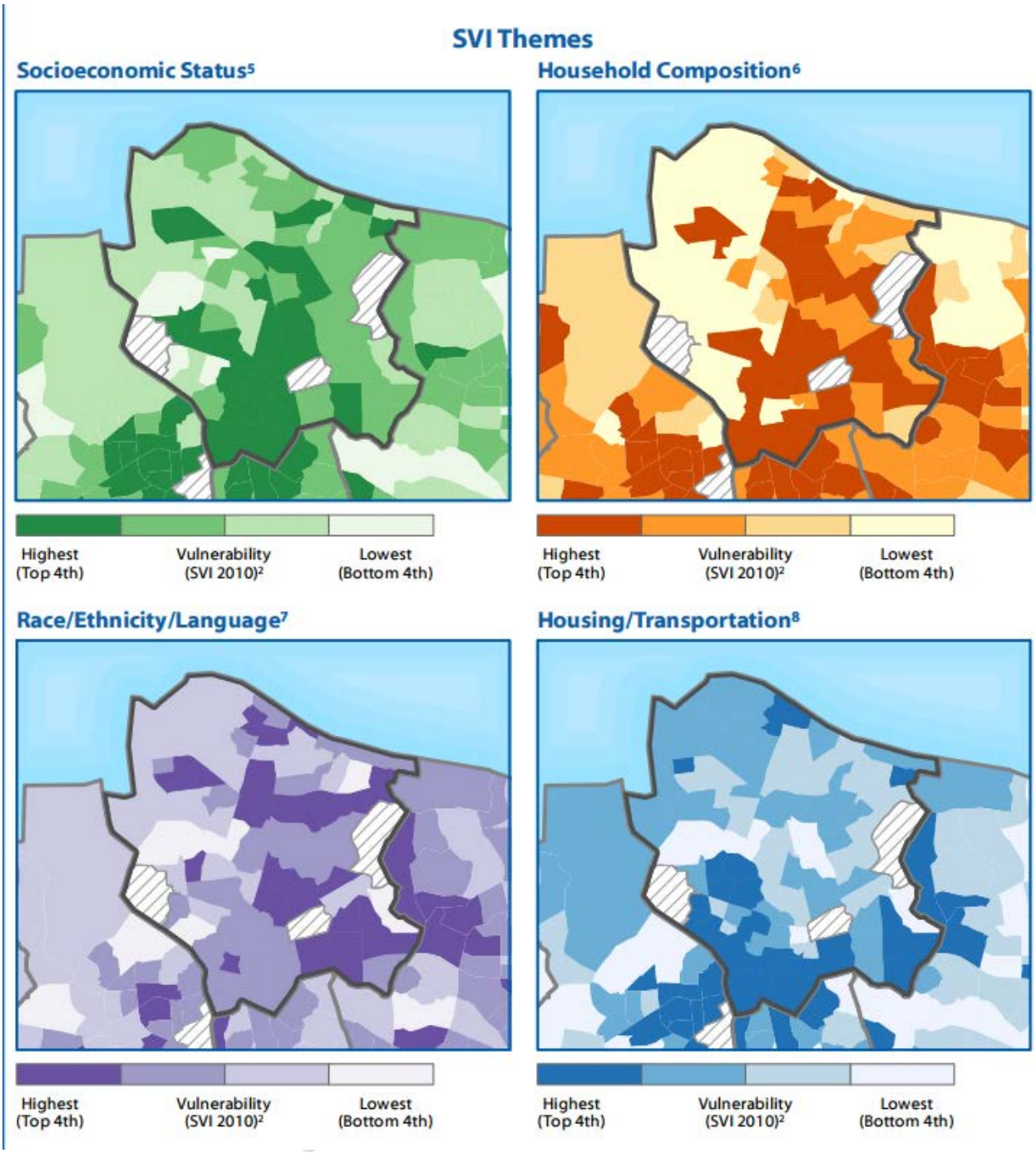


Figure 30. Theme-specific data on social vulnerability in Norfolk from the Social Vulnerability Index (Source: http://svi.cdc.gov/PreparedCountyMaps.html)

Availability of Private Insurance: Addressing the Public-Goods Character of Many Climate Events

Compounding the role of uncompensated repetitive flooding damages, and a 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.

A recent 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.[113] However, the researchers found that the private insurance payout amounted to only $33 billion (24%), with the largest share, $96 B (69%), paid out of the public coffers, as Table 30 shows.

Table 30. Allocation of the 2012 Hurricane Sandy cost burden. (Source: NRDC, May 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%

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. 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 31 lists these facilities that show the distinct public-goods character of many Norfolk critical infrastructure assets.

Table 31. Critical facilities in Norfolk. (Source: NOAA Coastal Economy Website)

[113] Daniel Lashof and Andrew Stevenson. *"Who pays for Climate Change? US Taxpayers Outspend Private Insurers Three-to-One to Cover Climate Disruption Costs."* NRDC, May 2013.

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

In a nutshell, to fully capture the extent of direct and indirect losses we need to quantify climate-related losses associated with costs of social vulnerabilities arising from income inequality, 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 the Sandia study, reported in Section4-2, 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.) However the study found that direct losses accounted only 38% of the total costs. When "indirect" costs that accounted for the remaining 62% 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.

5 – Adaptation: Decision Models and Selection of Candidate Projects

Adaptation serves as an overarching concept for the risk-based Resilience Framework the Volpe Center has developed for addressing infrastructure risks. Within this framework, adaptation encompasses all the actions undertaken to reduce infrastructure vulnerabilities, whether hazards of climate change, deteriorating infrastructure assets, or hazards of terrorist attacks or power outages. These actions, include the trio of adaptation measures—*Protection-Accommodation-Retreat*—recommended by IPCC, as reviewed in this section.

5-1 Adaptation Process and Alternative Measures

The Intergovernmental Panel on Climate Change (IPCC) has defined adaptation as an integrated and iterative process of *accommodation*, *engineering protection*, and *retreat*. One depiction of the IPCC notion of the climate change adaptation process is the IPCC working-group's recommended processes for quantifying the impacts of climate-change by measuring not only the atmospheric risks of climate change, but also the anthropogenic factors that exacerbate the impacts of atmospheric risks through energy and land-use practices, as depicted in Figure 31.

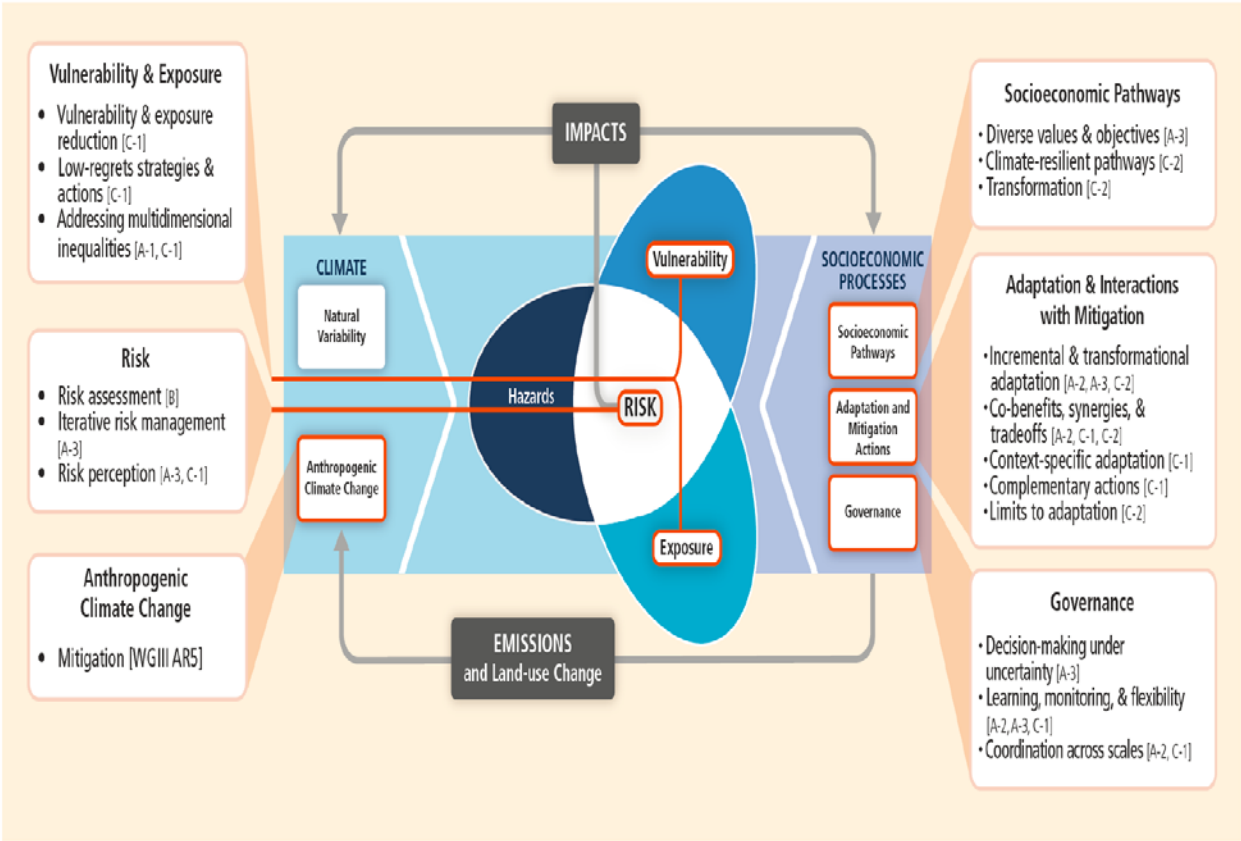


Figure 31. IPCC recommended process of planning for climate change adaptation. (Source: *Climate Change 2014: Impacts, Adaptation, and Vulnerability: Summary for Policy Makers,* IPCC, 2014)

Another perspective on climate adaptation strategies is presented by the U.S. Global Change Research Project (USGCRP), as shown in Figure 32, with its focus on two key components of climate adaptation planning: strategies that reduce the impacts, and those that mitigate the consequences.

Estimating the economic impacts of climate change involves a rigorous process of 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, *accommodation* strategies, and ultimate *retreat*. A *Resources for the Future* report has defined climate change impacts as a "change in welfare resulting from the event; with welfare evaluated *ex-post* as the compensation required to pay for the loss, or *ex-ante*, which accounts for uncertainty."[114] The following subsections in this report attempt to identify the dominant approaches to climate change adaptation in the HR region, by reviewing the processes and strategies recommended and implemented by NOAA, FHWA, New York City, and the City of Norfolk.

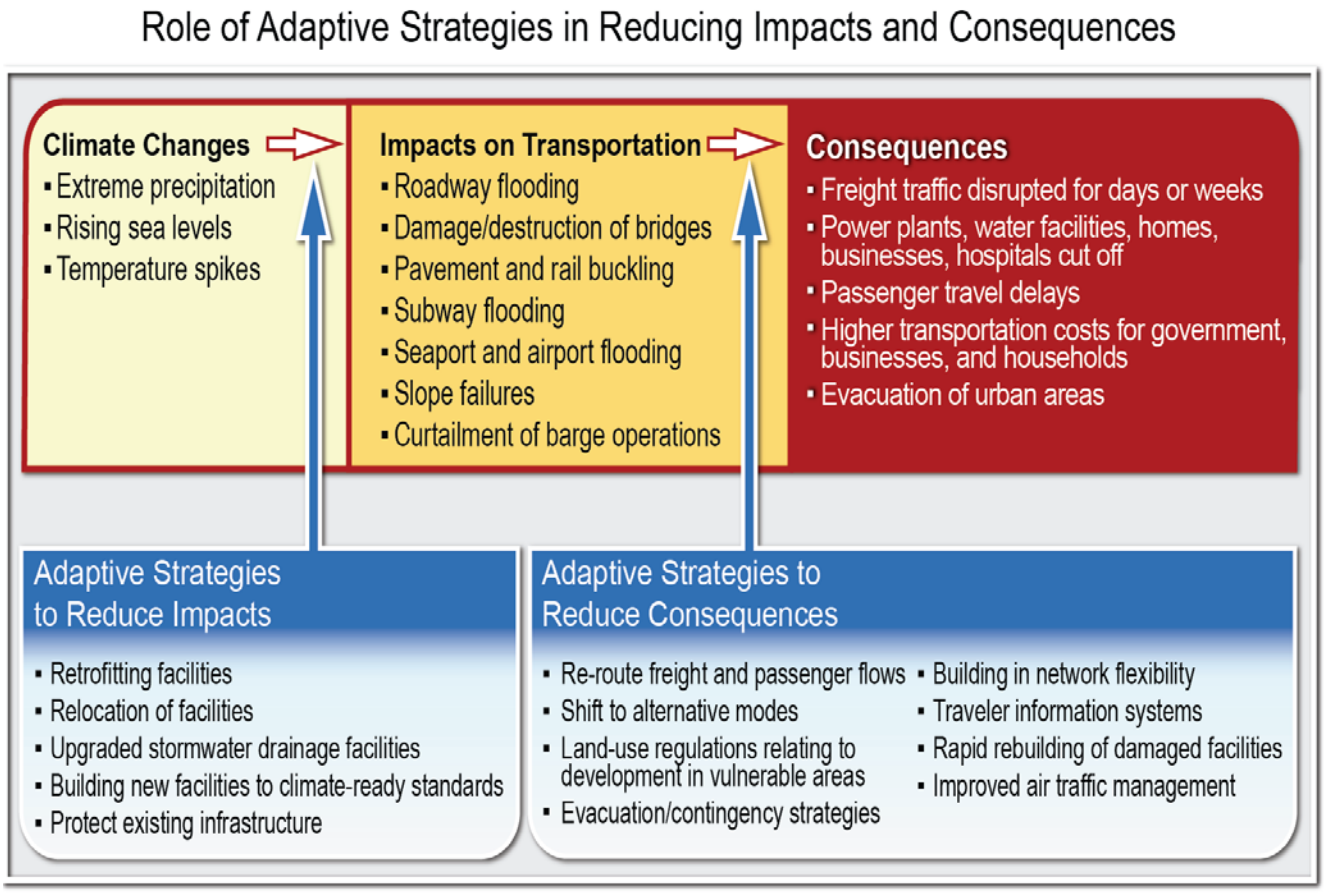


Figure 32. USGCRP view of climate change adaptation components. (Source: National Climate Assessment and Development Advisory Committee (NCADAC), U.S. Global Change Research Program (USGCRP), 2009)

NOAA Evaluation Template

NOAA's 2013 report offers a useful set of guidelines for the decision-processes to be followed for climate-change adaptation actions.[115] The report outlines the following actions and steps for the evaluation process:

[114] Carolyn Kousky. *Informing Climate Adaptation: A Review of the Economic Costs of Natural Disasters, Their Determinants, and Risk Reduction Options, Resources for the Future.* July 2012.
[115] *What Will Adaptation Cost? An Economic Framework for Coastal Community Infrastructure, Final Report.* Eastern Research Group, Inc. for NOAA, June 2013.

1. *Select Appropriate Local SLR Scenario*: Identify a set of SLR scenarios developed locally; choose a few years along the planning horizon to evaluate local SLR; calculate local SLR increases for the horizon year (Option: choose the USACE SLR Calculator);

2. *Develop High-Water-Level (HWL) Evaluation Scenarios to Identify a Range of HWL Assumptions*: Review historical data to select a range of high-water-level events. Integrate these data with SLR scenarios to select several water level height increases to use for the basis of the risk or impact assessment. Use the NOAA Extreme Water Levels Map[116] to find the "Exceedence Probability Curves" for the closest available location(s) and select the water level increase(s) to assess.

3. *Assess Exposed Infrastructure from No-Action Scenario*: Use water-level increases developed in previous task and NOAA Viewer to make a Reconnaissance Level Assessment of Expose areas; Determine the exposure (using NOAA, HAZUS-MH, and GIS Tools);

4. *Assess What You Can Do; Select Adaptation Strategies*: Review NOAA's Table 2.1 to identify possible action; based on cost of adaptation strategy, develop one or more action scenarios, with each scenario a least including 1 adaptation strategy.

5. *Calculate the Costs and Benefits*: This process involves the following steps:

    a. Identify potential impacts of disruptive events (Do-Nothing Option) and the impact of each option; tools include HAZUS-MH, NE Coastal Adaptation and SLR Tool (COAST); USACE's Depth Damage tools; parametric engineering cost tools; Create a list of primary (building/structural damage), secondary (business disruption), and environmental impacts (from NOAA's Table 3.1); list impacts of implementation: both positive and negative; brainstorm with community planners and engineers;
    b. Monetize the impacts: select tools and approaches; determine which tools are appropriate (NOAA Report's Appendix B: Tools); list the tools you will use for monetizing the impacts you've identified; Perform monetization; create tables to compile the total of all your monetized impacts; monetize all benefits and costs;
    c. Estimate the costs of implementing adaptation strategies. Get existing cost data about similar projects from your community; develop estimates of capital and maintenance costs; the timing of each project; plan for financing (Tool: parametric cost estimates), and;
    d. Make a decision: calculate total benefits of each action scenario and option.

[116] http://tidesandcurrents.noaa.gov/est/index.shtml.

NOAA's proposed evaluation template also includes a review of the range of costs to be considered for each water-level SLR scenario (3-ft, 8-ft, and 12-ft) and estimates of cost incurred in a "*No-Action Scenario*" for paying for Primary as well as Secondary damages. The Template contains five adaptation options:

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

NOAA's report describes 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: $2000-$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.

The FHWA Pilot 11-Step Adaptation Process

The proposed FHWA template referred to Section 1 of this report has been adopted by the ODU/HR Pilot Infrastructure Working Group (IWG) as the preferred evaluation template for HR Adaptation Decision Process. Several HR studies have attempted to incorporate RA/VA as well as a review of any on-going adaptation activities. The 11-step FHWA Pilot process for infrastructure climate change adaptation consists of the following steps:

1. Describe the site context: location-specific details such as surrounding land uses, population, economic activities, performance characteristics, proximal historic/sensitive

environmental resources; long-term transport and land-use plans, and whether they account for climate change;

2. Describe the existing/proposed facility; [pavement, bridge, dam, flood protection] with info on design/location/function/;
3. Identify climate stressors that may impact infra components (temps, SLR, precipitation, storms);
4. Decide on climate scenarios and determine the magnitude of changes: climate model projections that are used to determine whether and how much each of the variables of concern may change in the future;
5. Assess performance of the existing/proposed facility: whether the existing/proposed facility is performing as expected/modeled under current climate data and design assumptions and whether it will continue to do so under each of the possible future climate scenarios selected in step 4.
6. Identify adaptation option(s): potential planning, design, and maintenance operations options that would be used to address climate risks to the facility.
7. Assess performance of the adaptation options: performance under each potential climate change scenario selected in step 4; this analysis is similar to step 5 except that it is performed on the adaptation options instead of the existing facility or, in the case of new facilities, the standard design;
8. Conduct an economic analysis: evaluate how the benefits of undertaking a given adaptation option, defined as the costs avoided with adaptation, compare to its incremental costs under each of the possible future scenarios developed in step 4.
9. Evaluate additional decision-making considerations: identify other (non-engineering, non-economic) factors that should be considered before a final decision is reached;
10. Select a course of action: consider both economic and non-economic factors, weighing all the information presented, and select a course of action;
11. Plan and conduct ongoing activities: identify, plan for, and conduct ongoing activities (e.g., monitoring) using tools such as facility management plan.

New York City's Pre-Sandy Adaptation Framework

In 2008, New York City established an Adaptation Task Force that implemented an 8-step adaptation strategy that included all three of IPCC's *Protection*, *Accommodation*, and *Retreat* options, the *Climate Change Adaptation Task Force* of the *New York City Panel on Climate Change (NPCC).*[117] NPCC was convened by former New York City Mayor Michael Bloomberg as an independent advisory body composed of climate change scientists and experts in law, insurance, and risk management.

Established in 2008, the NPCC Task Force produced a foundation report and tools to identify infrastructure adaptation strategies. The product was called ClimAID,[118] a computerized model

[117] "New York City Panel on Climate Change (NPCC)." Georgetown Climate Center. See: http://www.georgetownclimate.org/organizations/new-york-city-panel-on-climate-change-npcc

[118] *Responding to Climate Change in New York State*. ClimAID, 2011.

of the pre-Sandy storm surge in New York City. The Task Force created ClimAID to model growing climate change risks to New York City from a broad range of climate change impacts. The NPCC Task Force recommended adaptation actions that ranged from incremental- to large-scale strategies, with planning horizons that ranged from short-term projects of less than 5 years to long-term projects of over 15 years. Closely following the five facets of adaption depicted in Figure 33.[119] The figure depicts the 8-step process developed for New York City climate change adaptation.

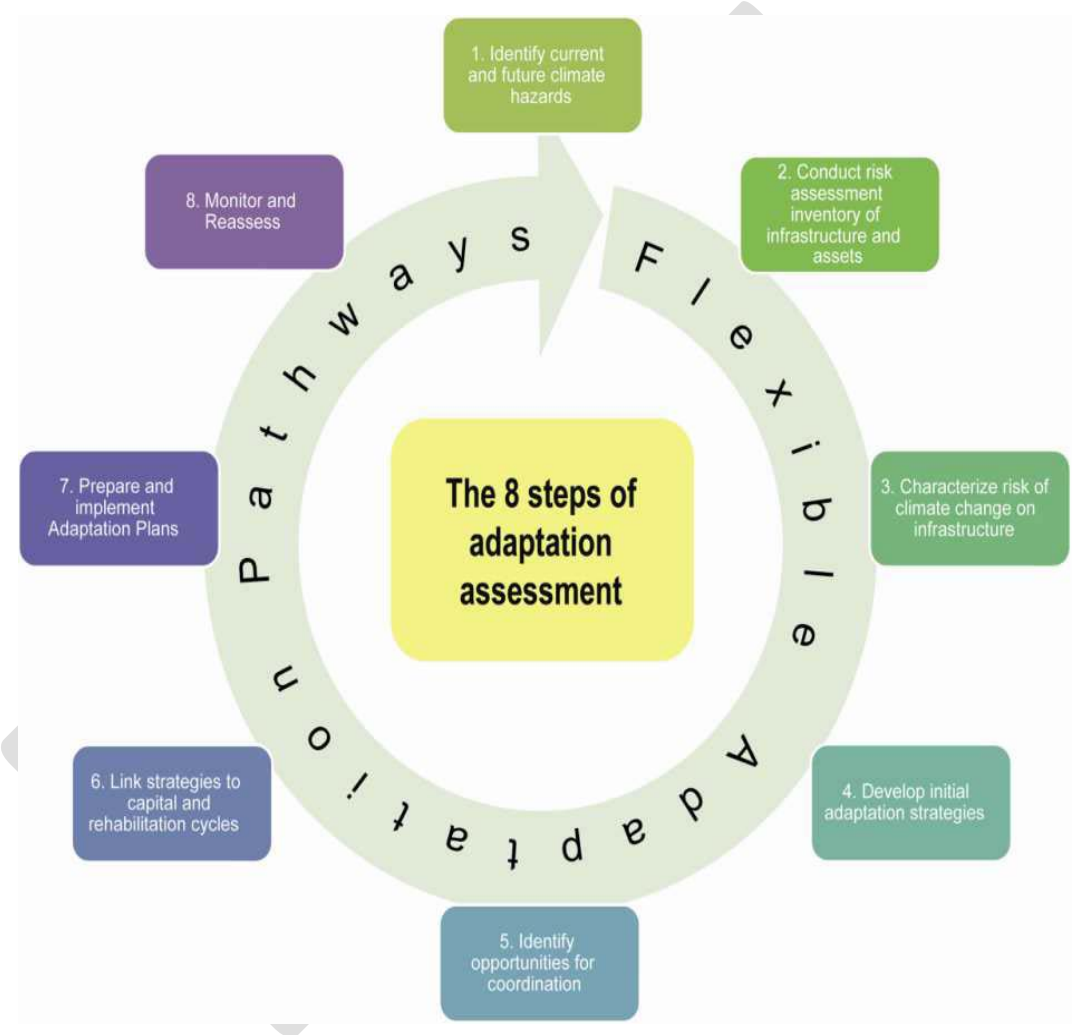


Figure 33. New York City Climate Change Adaptation Plan. (Source: NYC Panel on Climate Change Report, 2014)

[119] *Climate Change Adaptation in New York City: Building a Risk Management Response*. New York Academy of Sciences, 2010.

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 sea level rise;
- 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 Themes barriers.

Based on these modeling assumptions, the ClimAID report estimated the following consequences if adaptive strategies are not implemented:

- $10B in damage to transportation infrastructure from the 100-year flood projections;
- $50B in potential economic losses from transportation and utility outages and extended restoration times, plus loss of building stock; and
- Approximately 3 weeks of restoration time at $4B per day for various components of infrastructure to resume services.

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.

The City of Norfolk Candidate Adaptation Projects

The process for selecting candidate adaptation projects in HR is evolving. Illustrating an example of the evolving process is the City of Norfolk's activities in the past several years to undertake a systematic process of evaluating candidate adaptation options. Among these efforts is the *2012 City-Wide Drainage Study* [120] that identified the city's flooding risks and adaptation plans. The study identified a total of 253 drainage projects, and evaluated flooding

[120] *City of Norfolk, City-wide Drainage Master Plan, Final Submittal*. Timmons Group, Nov. 2012.

risks caused by tidal fluctuations, coastal storm surges and rain/precipitation. The scoring and prioritization criteria were based on the following eight criteria in Table 32.

Table 32. Prioritization criteria for Norfolk city-wide drainage study. (Source: *2012 City-Wide Drainage Study,* City of Norfolk)

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

The City of Norfolk also prepared a report on Coastal Resilience Strategy,[121] 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 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 $30M);
- The USACE study of the OceanView beaches for a flooding plan that involves Norfolk's first "*engineered beach*" (with the estimated construction cost of $18.4M with a city share of $5.5M; accounting for 30% 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.[122]

The engineering firm Fugro has also completed a study for the City of Norfolk for flooding mitigation. The study included major adaptation measures that 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

[121] *City of Norfolk, Coastal Resilience Strategy*, undated.

[122] Other estimates of adaptation costs: Wetlands Watch (Stiles, undated) 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.

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.

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 1% of the size of the city, but includes 584 structures, 523 of which are residential. Two of the three neighborhoods in the study, *The Hague and Pretty Lake* contain about 8,000 structures but do not have a tide surge control. 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. This is a capital project intended to protect against rainfall runoff. (area protected from tidal surge by an existing Tidal Gate 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.
- *Pretty Lake Flood Wall* – preliminary design; estimated cost: $50M
- *Mason Creek Pump Station* – cost: $30M (operated by the Navy);
- *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 project as

high as 2:1.[123] 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 33.[124]

Table 33. Proposed Norfolk flood control engineering projects. (Sources: *City Of Norfolk City-Wide Coastal Flooding Study,* Kevin Smith, Furgo, 2012*; Norfolk Flooding Strategy Update,* Presentation to Norfolk City Council, March 2012)

City of Norfolk Neighborhood	Proposed Adaptation and Mitigation Projects	Assessed Property Value in the Watershed	Estimated Cost	Project Cost as a % 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%

Another study on the Norfolk SLR adaptation projects is the case study of the Hampton Boulevard Corridor.[125] Hampton Boulevard starts along Norfolk Naval Station and leads to the Midtown Tunnel. Located along this route are also the Port Authority Police and ODU. The Boulevard is close to the Lafayette and Elizabeth rivers, making it vulnerable to flooding and inundation of 2-8 feet due to land subsidence, SLR, and high tide. The City of Norfolk and HRTPO officials decided to narrow down their evaluation focus on the Hampton Boulevard given its critical access point to the Naval Base and ODU, where inundation would disrupt traffic along the road for an extended period of time. The study team developed estimates of project cost and type, including:

[123] Although the city currently has a city-wide freeboard requirement of 1 foot, they are looking at increasing it. The City of Norfolk was the earliest jurisdiction in HR to reference the issue of sea level rise. 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.

[124] In Norfolk alone, a consultant has identified $1B in Protection improvements on the Lafayette Watershed in floodgates, berms and drainage improvements. (Source: ODU, State of the Commonwealth, 2015.)

[125] W. Richardson, Brian Smith. *An Investigation of Climate Change Adaptation: Case Study of the Hampton Boulevard Corridor in Norfolk, VA*. University of Virginia, 2015.

- *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; it also needs 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, two projects in Norfolk, the Blue Bird Park and Wetland construction project, at an estimated cost of $84,500 is currently in 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 Wall will range from 3 to 10 feet in height and cost $10 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, 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 Hurricane Barrier in Connecticut. (The project costs are expected to be less than the more elaborate Craney Island Barrier.)

6 – Scoping the Boundaries of the Future Tasks

This final subtask highlights the key issues that need to be addressed in Task 1-b and the future pilot efforts. The task so far has provided a baseline overview of the region's transportation infrastructure—with focus on the City of Norfolk—and the identified vulnerabilities of the region's built infrastructure and residents. The scope of Task 1-b will include the following components:

Application of the Volpe Center Resilience Framework to the Scope of the Pilot: The scope of Task 1-b will include expanding the analysis beyond the baseline condition inventory to include a broader infrastructure resilience approach. For this, the Volpe Center will build on its Resilience Framework to conduct a full scale analysis of the Pilot region's transportation risks and cost-effective mitigation and adaptation measures to be adopted. This approach is likely to serve as a *force multiplier* since it will incorporate the risk-management goals of other federal agencies for long-term adaptation and mitigation planning, including NASA, DHS, DOT, USACE, and EPA.

The 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.[126] Coupled with the overarching adaptation process that is embedded in the Volpe Center Resilience Framework, there is also a rigorous, proactive decision-support perspective that views risk management and adaptation planning within the context of a systematic risk mitigation and portfolio-investment planning. This proactive decision-making process will be fully explored in the future phases of the HR Pilot adaption projects and investment decision.

Figure 34 depicts the application of prevention-protection-adaptation-mitigation measures embedded in the Volpe Center Infrastructure Resilience Framework 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.

[126] See the Volpe Center report on a Risk-based Framework for Infrastructure Resilience: http://ntl.bts.gov/lib/47000/47800/47848/Infrastructure_Resiliency_Final_Revised_July_10.pdf

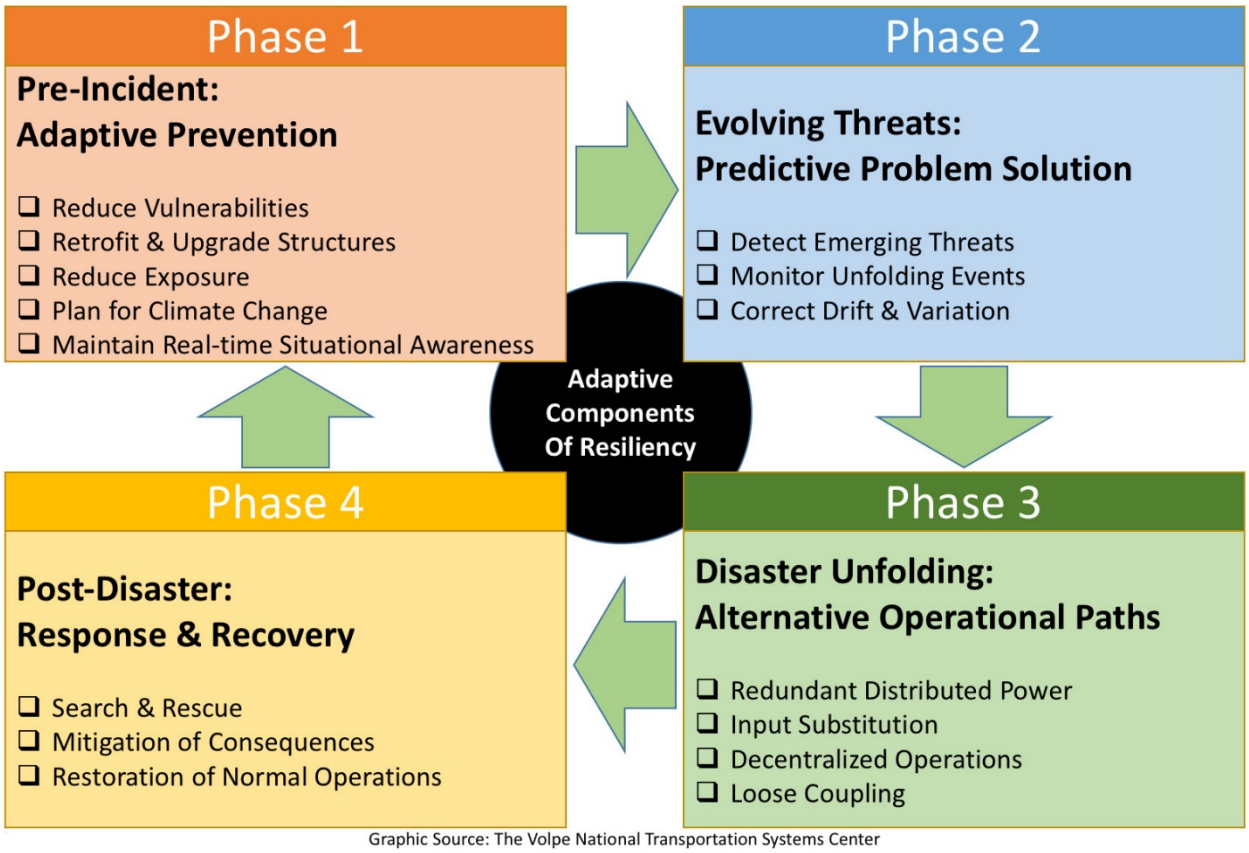


Figure 34. Adaptation components of the Volpe Center Resilience Framework. (Source: Volpe Center)

Expanded Modal Focus: The approach of Task 1a has been a high-level focus on risk-assessment and quantification of the economic impacts of climate-related disruptions. For the initial scope of the study, no specific evaluation of the merits of each adaptation measure or assessment tool has been conducted. In this respect, the study has relied fully on the evidence provided by the region's planning organizations for addressing transportation planning priorities. For the future scope of the study, to the extent that specific adaptation measures enter the mix of improvements being evaluated, the focus will be downscaled, upon the decision of the Pilot team, to allow evaluation of specific impacts of improvement measures. Some of these transportation related issues include:

- Addressing the role of the region's freight railroads in enhancing the resilience of region's transportation network to disruption. In parallel with this, an evaluation of the existing vulnerabilities in the private rail industry's tracks and asset condition will be conducted;

- A greater focus on mode-specific climate sensitivity of the transportation network. In this respect, measures of sensitivity for transportation systems would be developed in

terms of inter-connected "network sensitivity" levels. Some of the potential products of this approach would be identification of alternate routes and modes when a particular asset is disrupted.

- Addressing the role of transportation in the regional economy, including the direct and indirect impacts on employment and income and transport-sensitive sectors such as tourism.

Closing Data Gaps: The study will explore the gaps in the application of economic impact models to assessment of the region's infrastructure resilience. It will also explore the need to close the existing data gaps if the future scope of the pilot requires downscaling to a greater resolution of data at the sub-region level, using the available public databases and GIS tools to achieve that goal.

Expanded Tools and Models: The next study phase will explore the need for an in-depth focus on specific tools and capabilities, contingent of the Pilot's evolving needs. This may involve study will place a greater emphasis on tools such as EPA's CIRA tool, the NCHRP CAPTA/CapTool; NASA's CASI tool, and Sandia's REAcct tool if recommended by the Pilot working groups, e.g., the Economics (EIAC). Also, depending on the strategies adopted by the EIAC more rigorous economic methods such as CGE will be developed, in collaboration with ODU, to examine economic impacts of specific scenarios on the regional economy.

Collaboration with NASA: Opportunities for beneficial collaboration with NASA's are to be explored, given the agency's extensive engagement in addressing climate change risks—with respect to both research priorities and adaptation planning for DOD agencies that are directly at risk of SLR and flooding inundation in Hampton Roads. Another potential partner in NASA are those addressing the value of information for their CLARREO climate satellite mission, which is based in part on the social cost of carbon.[127]

Collaboration with ODU: Opportunities for joining forces to address key research issues that are of interest for both ODU and DOT will be explored. These include working with ODU and the EIAC to use economic impact models such as IMPAN and methodologies such as CGE to evaluate the long-term infrastructure investment options for preventive adaptation and risk mitigation. In addition to economic modeling, collaboration with ODU will enable the Pilot to address critical findings of the ODU *2015 State of the Commonwealth Report,* including building on the ODU findings on the social vulnerabilities that arise from fluctuations in GDP growth and rising rates of income inequality in the region, and evaluate them as a potential risk factor for

[127] Cooke, Roger et al. *Value of information for climate observing systems*. Resources for the Future, Washington, DC; NASA Langley Research Center, Hampton, VA, July 2013.

climate change disruption. Collaborative efforts will include ensuring relevance to the ODU HR Pilot process, including other parallel efforts to study economic impacts regionally across other sectors, such as energy, that impact transportation resiliency.

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

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

DRAFT

Appendix B – References

Analysis Group, The Economic Impacts of the Regional Greenhouse Gas Initiative on Ten Northeast and Mid-Atlantic States: Review of the use of RGGI Auction Proceeds from the First Three-Year Compliance Period, Hibbard, et. al. November 15, 2011.

Argonne National Laboratory, Climate Change Adaptation Capabilities, Risks and Infrastructure Science Center (RISC), HR Intergovernmental Planning Org Briefing, March 13, 2015; downscaled RRAP climate data;

Argonne National Laboratory, *Resilience Measurement Index: An Indicator of Critical Infrastructure Resilience,* Decision and Information Sciences Division, 2013.

Argonne National Laboratory, Resilience: Theory and Application, Decision and Information Sciences Division, 2012.

Atkinson, Larry et, al, "Sea Level Rise and Flooding Risk in Virginia", Sea Grant Law and Policy Journal, Vol. 5, No. 2, 2013.

EPA Chesapeake Bay Program, Science and Technology Advisory Committee White Paper, Pyke, et.al. Climate Change and the Chesapeake Bay, US Annapolis, MD., 2008.

EPA, *Climate Change in the United States: Benefits of Global Action*, 2015.

EPA, *Climate Change in the United States: Benefits of Global Action,* 2015.

EPA, Climate Change Adaptation Plan, Draft, June 2012

FHWA, Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: The Gulf Course Study, Phase 2; Task 3.2: Engineering Assessments of Climate Change Impacts and Adaptation Measures, August 2014; FHWA-HEP-15-004;

FHWA, "Assessing Vulnerability and Risk of Climate change Effects on Transportation Infrastructure: Pilot of the Conceptual; See: http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/vulnerability_assessment_pilots/conceptual_model62410.cfm

Georgetown Climate Center, Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Road.

Haimes, Yacov Y., et. al. Assessing and Managing Risk of Terrorism to Virginia's Interdependent Transportation Systems, Center for Risk Management of Engineering Systems (CREMS), University of Virginia, October 2004.

HRPDC Climate Change in Hampton Roads, Phase III: Sea-Level Rise in Hampton Roads, VA,

HR Vision – Annual Report, Sept. 30, 2013, Prepared by HR Partnership

HRTPO (Transportation Planning Organization) HR Regional Bridge Study, 2012.

HRTPO, Hampton Roads Regional Freight Study, 2012 Update, September 2012

HRTPO, Hampton Roads Military Transportation Needs Study: Roads Serving the Military and Sea Level Rise/Storm Surge, July 2013

ICF International, *Virginia Airport System Economic Impact Study: Technical Report,* Prepared for Virginia Department of Aviation, August 2011.

IPCC, *Climate Change 2014: Impacts, Adaptation, and Vulnerability: Summary for Policy Makers,* March 31, 2014. https://ipcc-wg2.gov/AR5/images/uploads/IPCC_WG2AR5_SPM_Approved.pdf

Jacobs Consultancy, *Economic Impact Study -2004, Norfolk International Airport*, Prepared for Norfolk Airport Authority, October 2007.

Kirshen, Paul, et al., "Simplified Method for Scenario-based risk assessment adaptation planning in the coastal zone" 2011, In "Climate Change: An Interdisciplinary international journal, 2011.

Montibeller, Gilberto and A. Franco, Ch. 2, "Multi-Criteria Decision Analysis for Strategic Decision Making, in Handbook of Multi-criteria Analysis, 2010. Schroader, Puke, Kavetski, Scenario-based MCDA;

NASA, Robert Pearce, NASA's Aeronautics Research Strategy: A Reflection of Research Continuity, Strategic Analysis, And Community Dialogue, NSAA Aeronautics Research Mission Directorate IARMD), undated PPT Presentation.

NASA, *Climate Risk Management Plan: Managing Climate Risks and Adaptation to a Changing Climate*, 2014.

NASA, Langley, Making Space for the Future, 2006.

NASA, Rosenzweig, et.al., 2011, NASA's CASI: Building Climate Resilient NASA Center, *Livebetter* Magazine, Dec. 2011.

NCHRP, *Costing Asset Protection: An All Hazards Guide for Transportation Agencies (CAPTA),* Report 525, Surface Transportation Security Volume 15, 2009.

New York Academy of Sciences, "Climate Change Adaptation in New York City: Building a Risk Management Response, 2010.

NOAA, *What Will Adaptation Cost? An Economic Framework for Coastal Community Infrastructure*, Final Report, Eastern Research Group, Inc. June 2013.

NOAA, http://www.nhc.noass.gov/surges/slosh.php; http://www.nhc.noaa.ssurge/ssurge_slosh_shtml

NOAA, Office of Coastal Management, Jeff Payne, Testimony to the House Committee on Homeland Security, November 21, 2014.

Norfolk, City of, City-wide Drainage Master Plan, Final Submittal, Nov 8, 2012, By Timmons Group.

Norfolk, City of, Kevin Smith, Fugro Atlantic, presentation on "City Of Norfolk City-Wide Coastal Flooding Study, February 29, 2012. For specific project cost figures, see Presentation to Norfolk City Council,

Norfolk Flooding Strategy Update", March 27, 2012

NRDC, Daniel Lashof and Andrew Stevenson, "Who pays for Climate Change? US Taxpayers Outspend Private Insurers Three to One to cover Climate Disruption costs, May 2013

ODU, Strome College of Business, 2015 State of the Commonwealth Report, December 2015

Old Dominion University (ODU), Hampton Roads – Crater Multimodal Transportation and Distribution Study, December 2011.

Resources for the Future (RFF), Carolyn Kousky "Informing Climate Adaptation: A Review of the Economic Costs of Natural Disasters, Their Determinants, and Risk Reduction Options," July 2012, RFF-DP-12-28

Rose, Adam, and S. Lia "Modeling regional economic resilience to disasters: A Computable General Equilibrium (CGE) analysis of water service disruption", Journal of Regional Science, 45 (1): 75-112, 2005.

Rutgers University, Judd Schechtman and Michael Brady, Cost Efficient Climate Change Adaptation in the North Atlantic, Project supported by NOAA, 2013. www.regions.noaa.gov/north-atlantic/wp-content/uploads/2013

Sandia National Laboratories, Development of an Urban Resilience Analysis Framework: 2 - Application to Norfolk, VA, October 19, 2015.

Sandia National Laboratories, Regional Economic Accounting (REAcct): A Software Tool for Rapidly Approximating Economic Impacts, July 2011.

Titus, et al. "Greenhous Effect and SLR: the Cost of Holding Back the Sea." *Coastal Management*, Vol. 19, (1991).

USACE Risk Management Strategy for Norfolk Naval Station, Environmental Laboratory, Kelly Burkes-Copes, Quantifying Coastal Storm and SLR Risks to Naval Station Norfolk, U.S. Army Engineers R&D Center (ERDC), October 17, 2014.

USACE, North Atlantic Coast Comprehensive Study: Resilient Adaptation to Increasing Risk, Main Report, Final Report, January 2015

U.S. Global Change Research Program (USGCRP), the National Climate Assessment and Development Advisory Committee (NCADAC), 2009.

Virginia Institute of Marine Science (VIMS), Center for Coastal Resource Management, William and Mary University, Recurrent Flooding Study for Tidewater Virginia, January 2013.
Virginia Surface Transportation Plan, 2005

VDOT, Climate Change Adaptation Case Studies: Hampton Roads, VDOT, Climate adaptation
http://www.fhwa.dot.gov/environemnt/climate_change/adaption_studies/hampton_roads/index.cfm

Virginia Governors' Commission on Sea-Level Rise, 2008
http://www.sealevelrisevirginia.net/docs/CC_meeting_agendas_notices/CCC_Final_Draft_Findings_111108.pdf

Volpe Center report on a Risk-based Framework for Infrastructure Resilience, 2014
http://ntl.bts.gov/lib/47000/47800/47848/Infrastructure_Resiliency_Final_Revised_July_10.pdf

Wetlands Watch, William A. Stiles, A "Tool Kit" for SLR Adaptation in Virginia, undated report,

World Resources Institute, http://www.wri.org/sites/default/files/wri_factsheet_virginia_final.pdf

DRAFT

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 TM) [128]	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 TM 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 Climate Data Center (NCDC) 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

[128] See Appendix B for more detail on SHELDUS

National Transportation Atlas Database	Alternative source of HR asset data inventory for comparison with HAZUS-MH data. The National Transportation Atlas Database is a set of nationwide geographic databases of transportation facilities, transportation networks, and associated infrastructure, hosted by the Bureau of Transportation Statistics (BTS). These datasets include spatial information for transportation modal networks and intermodal terminals, as well as the related attribute information for these features. www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_atlas_database/index.html
Virginia Statewide Road Centerline File	Virginia DOT statewide road centerlines geodatabase and shapefile. The Virginia Geographic Information Network (VGIN) has coordinated and manages the development of a consistent, seamless, statewide digital road centerline file with address, road name, and state route number attribution as part of the Virginia Base Mapping Program (VBMP). The Road Centerline Program (RCL) leverages the Commonwealth's investment in the VBMP digital orthophotography and is focused on creating a single statewide, consistent digital road file. The RCL data layer is a dynamic dataset supported and maintained by Virginia's Local Governments, VDOT, and VGIN. VBMP RCL is extracted and provided back to local governments and state agencies in many geographic data sets every quarter. http://www.arcgis.com/home/item.html?id=4ac9fed31dbb485397c5349b7544aecb
Virginia Institute of Marine Science (VIMS)	The Center for Coastal Resources Management (CCRM) within the Virginia Institute of Marine Science (VMIS) has been researching the effects of regional climate and coastal stressors for several years and has a number of climate change and sea level rise projects, such as a recurrent flooding study for tidewater Virginia. The studies are available on their website. http://ccrm.vims.edu/coastal_zone/climate_change/
HR Planning District Commission (HRPDC)	HRPDC provides a number of resources on their website, including studies on HR transportation assets, condition, and economy; maps of commuting flows and other regional characteristics; and other information. http://www.hrpdcva.gov/
Norfolk Open GIS Website	City of Norfolk's GIS Open Data Site contains various spatial data covering a number of different sectors. The City's datasets are updated regularly and can be downloaded or accessed for free. The Norfolk road network shows attributes such as functional classification. http://data.orf.opendata.arcgis.com/

DRAFT

HAZUS 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 7.2 Highway Single-span Bridge Damage Relationship

Flood Return Period	Scour Potential[(1)]/Probability of Failure (percent)				
	1	2	3	4-8	9
100-year	5	2	1	0	N/A
500-year (2x 100-year probability)	10	4	2	0	N/A
1000-year (1.5x 500-year probability)	15	6	3	0	N/A

The Scour Potential is a field in the Hazus Bridge database and is from the FHWA inventory of bridges

Table 7.3 Highway Continuous-Span Bridge Damage Relationship

Flood Return Period	Scour Potential[(1)]/Probability of Failure (percent)				
	1	2	3	4-8	9
100-year	1.25	0.5	0.25	0	N/A
500-year (2x 100-year probability)	2.5	1	0.5	0	N/A
1000-year (1.5x 500-year probability)	3.75	1.5	0.75	0	N/A

[(1)] The Scour Potential is a field in the Hazus Bridge database and is from the FHWA inventory of bridges

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.

DRAFT

Bridge Standards

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 are also more likely to be occasionally flooded or have approaches that are difficult to navigate. However, they are not inherently unsafe.

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-posed 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 don not in fact become scour critical. Currently no bridges in HR are classified as such.

Sufficiency Rating: Numerical ratings for each bridge based on its structural evaluation, design and function, and public importance. The yield a number value between 0% and 100%, with a sufficiency rating of 100% representing an entirely sufficient bridge. The method for calculating bridge sufficiency ratings is complex. Scores for each of the four components:

- Structural adequacy and safety (55%): includes condition of the superstructure, substructure and culvert;
- Serviceability and functional obsolescence (30%): includes 13 factors related to design and function of the bridge;
- Essentiality for public use (15%: includes traffic volumes carried on the structure, detour length, and the importance of the route carried by the structure for military deployment;
- Special reductions (up to 13% reduction: the rating can be reduced based on the type of structure, safety features.

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.[129]

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.

Appendix D – Economic Analysis Tools

The I-O data will enable calculation of business losses due to events relating to both direct property damage losses and business interruption losses due a facility's (port, bridge, tunnel, highway) shut-down, unavailability of the facilities for use as business or work-travel, as well as longer term losses resulting from reduced revenues for businesses such as hospitality or tourism. Here are the 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 # 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 multiplies translate a dollar of direct economic impact in a region/industry into a total economic impact. These multiplies 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.

[129] (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.)

Regional Input-Output Multiplier System (RIMS II)

RIMS II, developed and maintained by the DOC, is a for-fee data service by the 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.[130] 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).[131] The model is based on an I-O spreadsheet table that shows the industrial distribution of inputs purchased and inputs sold for any industry sector. The inputs purchased 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 waves of activity that affects the entire regional economy. RIMS II's advantage is that it uses readily available BEA data sources, is a simple to use spreadsheet-based tool, and is relatively inexpensive, costing between $2K and $5K.

IMPLAN Model

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.[132] 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

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

[131] (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.)

[132] 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.

and has the advantage of allowing a dynamic application of the multipliers to the impacted industries.

Regional Economic Models, Inc. or 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.[133]

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.[134]

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 assts. 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 non-linear research tools that have behavioral content and could potentially mimic the role of markets and prices. To this extent, CGE models overcome the limitation of I-O models that work only for existing infrastructure and a non-growth scenario.

[133] http://citizensclimatelobby.org/wp-content/uploads/2014/06/REMI-carbon-tax-report-62141.pdf.

[134] Adam Rose and S. Lia, "Modeling Regional Economic Resilience to Disasters: A Computable General Equilibrium Analysis of Water Service Disruptions," *Journal of Regional Science*, 45(1):75-112, 2005.