TECHNICAL GUIDE: DEVELOPMENT AND MONITORING OF VTRANS LONG-TERM RISK & OPPORTUNITY REGISTER

VTRANS | VIRGINIA'S TRANSPORTATION PLAN

PREPARED BY THE OFFICE OF INTERMODAL PLANNING AND INVESTMENT FOR THE COMMONWEALTH TRANSPORTATION BOARD

DRAFT September 2021

VIRGINIA COMMONWEALTH TRANSPORTATION BOARD MEMBERS

FOR MORE INFORMATION

Visit vtrans.org for additional details, updates, and documentation about the VTrans development process.

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PREPARED BY THE OFFICE OF INTERMODAL PLANNING AND INVESTMENT FOR THE COMMONWEALTH TRANSPORTATION BOARD

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LIST OF ACRONYMS

AADT	Annual Average Daily Traffic
AC	Activity Center
ACS	American Community Survey
ADAS	Advanced Driver Assistance Systems
ADS	Automated Driving Systems
AEB	Automatic Emergency Braking
B2B	Business-to-Business sales (Wholesale trade)
B2C	Business-to-Consumer sales (Retail trade)
BCI	Backup Collision Intervention
BEV200	Battery Electric Vehicle with 200-mile range
BEV300	Battery Electric Vehicle with 300-mile range
BLS	US Bureau of Labor Statistics
BRT	Bus Rapid Transit
BSW	Blind Spot Warning
CACC	Cooperative Adaptive Cruise Control
CAGR	Compound Annual Growth Rate
CAV	Connected and Automated Vehicles
CDOT	Colorado Department of Transportation
CICAS	Cooperative Intersection Collision Avoidance System
CO	Carbon Monoxide
CO2e	Carbon Dioxide Equivalent Greenhouse Gas Emissions
CoM	Coefficient of Imitation
CoN	Coefficient of Innovation
CoSS	Corridor of Statewide Significance
COVID-19	Coronavirus Disease 2019
CTB	Commonwealth Transportation Board
CTB	Commonwealth Transportation Bard
DOTs	Department of Transportation
DNPW	Do Not Pass Warning
DRPT	Department of Rail and Public Transportation
DSRC	Dedicated Short-range communication service
EEA	Equity Emphasis Area
EPS	Energy Policy Simulator
ESC	Electronic Stability Control
EV	Electric Vehicles

FCW	Forward Collision Warning
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIRM	Flood Insurance Rate Map
FMCSA	Federal Motor Carrier Safety Administration
GHG	Greenhouse Gas
GMSL	Global Mean Sea Level
HBW	Home-based Work Trip
HEV	Hybrid Electric Vehicle
HRPDC	Hampton Roads Planning District Commission
ICEV	Internal Combustion Engine Vehicle
IF	Importance Factor
IPCC	Intergovernmental Panel on Climate Change
LCW	Lane Changing Warning
LEHD	Longitudinal Employer-Household Dynamics
LKA	Lane Keeping Assist
LODES	LEHD Origin-Destination Employment Statistics
MassDOT	Massachusetts Department of Transportation
MPO	Metropolitan Planning Organization
MSA	Metropolitan Statistical Area
NACTO	National Association of City Transportation Officials
NAICS	North American Industry Classification System
NBI	National Bridge Inventory
NCEI	National Centers for Environmental Information
NHC	National Hurricane Center
NHSTA	National Highway Traffic Safety Administration
NHTS	National Household Travel Survey
NOAA	National Oceanic and Atmospheric Administration
NOx	Nitrogen Oxides
NSC	National Safety Council
OIPI	Office of Intermodal Planning and Investment
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Matter
PMT	Person-miles Traveled
RAC	Residence Area Characteristics
RDCW	Road Departure Crash Warning

RN	Regional Network
ROC	Ratio of Concentration
SAE	Society of Automotive Engineers
SANDAG	San Diego Association of Governments
SLOSH	Sea, Lake and Overland Surges from Hurricanes
SLR	Sea Level Rise
SOC	Standard Occupational Classification
SOV	Single-Occupant Vehicle
SUV	Sport Utility Vehicle
TDM	Transportation Demand Management
TMC	Traffic Message Channel
UAV	Unmanned Aerial Vehicles (also called drones)
US DOT	United States Department of Transportation
USGCRP	U.S. Global Change Research Program
V2Cyclist	Vehicle to Cyclist
V2I	Vehicle-to-Infrastructure
V2Pedestrian	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VAST	Vulnerability Assessment Scoring Tool
VBRSP	Virginia Business Ready Sites Program
VDOT	Virginia Department of Transportation
VFRMS	Virginia Flood Risk Management Standard
VGIN	Virginia Geographic Information Network
VIMS	Virginia Institute of Marine Sciences
VMT	Vehicle-miles of Travel
VOC	Volatile Organic Compounds
VTRC	Virginia Transportation Research Council
WAC	Workplace Area Characteristics

DEFINITIONS

- Automated Vehicles – NHTSA[1] defines automated vehicles as those in which at least some aspects of a safety-critical control function (e.g., steering, acceleration, or braking) occur without human driver input.
- Autonomous Vehicles – The California DMV[2] defines an autonomous vehicle based on the technology modes used for vehicle operation. Autonomous technologies are a combination of hardware and software, remote and/or on-board, that has the capability to drive a vehicle without active physical control or monitoring by a human operator. Autonomous mode is the status of vehicle operation where autonomous technology performs the dynamic driving task, with or without a human actively supervising the autonomous technology's performance of the dynamic driving task. An autonomous vehicle is operating or driving in autonomous mode when it is operated or driven with the autonomous technology engaged.
- Levels of Automation – The Society of Automotive Engineers (SAE) has defined levels of driving automation as a way to describe the specific roles played by the human, the driving automation system and other vehicle systems to perform the dynamic driving task. Six levels of automation are identified. SAE J3016,[3] which defines these levels, has become the de facto standard of levels of automation.
  - SAE Level 0 Automation – Human driver with driver support features providing warnings and momentary assistance.
  - SAE Level 1 – Human is driving with steering OR brake/acceleration control support.
  - SAE Level 2 – Human is driving with steering AND brake/acceleration support.
  - SAE Level 3 – Human is NOT driving when automated driving systems are engaged. When system requests, human MUST drive.
  - SAE Level 4 – Human is NOT driving when automated driving systems are engaged. The automated driving system will not request a human to take over driving. The automated features are restricted to specific conditions and will not drive unless all conditions are met.
  - SAE Level 5 – Human is NOT driving when automated driving systems are engaged. The automated driving system will not request a human to take over driving.
- Cohort[2] – A group of individuals having a statistical factor (such as age or class membership) in common in a demographic study
- Connected Vehicles – USDOT[4] defines Connected Vehicle (CV) technologies as equipment, applications, or systems that use V2X communications to address safety, system efficiency, or mobility on our roadways. The concept uses data from short-range communication broadcasts and peer-to-peer exchanges within approximately 300 meters to "sense" what other travelers (vehicles, bicyclists, pedestrians, wheelchairs, motorcycles, buses, trucks, and others) are doing and identify potential hazards.
- Driver[5] – For the purpose of this document, the term "driver" refers to developments causing change, affecting or shaping the future. A driver is the cause of one or more effects.
- E-commerce – Trade conducted through the internet as the primary means of communication and sale
- Emissions – By-products of internal combustion engines, such as greenhouse gases and other pollutants
- Macrotrend[6] – An emerging pattern of change likely to impact state government and require a response. More than one macrotrend can be associated with a megatrend.
- Megatrend[5] – A large social, economic, political, environmental or technological change that is slow to form.
- Micromobility – Travel via small personal vehicles, such as scooters, bicycles, skateboards, etc.
- Opportunity – A situation or scenario wherein there is some uncertainty and at least some probability of a positive outcome or result.

[1] National Highway Traffic Safety Administration

[2] State of California Department of Motor Vehicles Autonomous Vehicle Definitions

[3] SAE International, "SAE International Releases Updated Visual Chart for Its "Levels of Driving Automation" Standard for Self-Driving Vehicles", December 11, 2018.

[4] USDOT, How Connected Vehicles Work

[5] European Foresight Platform

[6] Transportation Policy Task Force Suggested State Legislation Docket. 2009. California

- Resiliency[1] – The capability to anticipate, prepare for, respond to and recover from extreme weather event(s) with minimum damage to social well-being, infrastructure, the economy, and the environment.
- Risk – A situation or scenario wherein there is some uncertainty and at least some probability of a negative outcome or result.
- Risk & Opportunity Register – Listing of uncertainties that will also include some level of prioritization for the Commonwealth to consider mitigation, avoidance, transference, or acceptance strategies.
- Sea Level Rise – Incremental rising of the mean high water level over time.
- Shared Mobility – The shared use of a vehicle, motorcycle, scooter, bicycle, or other travel mode. Shared mobility provides users with short-term access to one of these modes of travel as they are needed.[2]
- Storm Surge[3] – Abnormal rise in seawater level during a storm, measured as the height of the water above the normal predicted astronomical tide.
- Vulnerability[4] – Vulnerability is a function of exposure to a hazard(s), the sensitivity to the given hazard, and adaptive capacity or the system's ability to cope.
- Workplace Flexibility – The ability to work at home or in a location other than the employer office or jobsite through the use of internet, email, and telephone.
- KABCO Scale[5] – The "KABCO" injury scale can be used for establishing crash costs. This scale was developed by the National Safety Council (NSC) and is frequently used by law enforcement for classifying injuries:
  - K – Fatal injury;
  - A – Severe injury;
  - B – Visible injury;
  - C – Non Visible injury; and
  - O – Property Damage Only

[1] This is a draft definition developed by the Office of Intermodal Planning and Investment (OIPI), pending feedback from the Commonwealth Transportation Board. For more details, please refer to Appendix 1.

[2] SAE International, JJ3163 – Taxonomy and Definitions for Terms Related to Shared Mobility and Enabling Technologies. Accessed on July 8, 2021.

[3] National Oceanic and Atmospheric Administration. What is storm surge? Accessed on July 8, 2021.

[4] This is a draft definition developed by the Office of Intermodal Planning and Investment (OIPI), pending feedback from the Commonwealth Transportation Board. For more details, please refer to Appendix 1.

[5] National Safety Council

1. PURPOSE OF THE TECHNICAL GUIDE

This Technical Guide is a synthesis of technical methods and processes used to execute the Draft Policy for the Development and Monitoring of the VTrans Long-term Risk & Opportunity Register as outlined in the Chapter 6 of the VTrans Policy Guide. This Technical Guide is developed for planners, engineers, and other professionals interested in the data sources, processes, and methods used to implement the CTB's policies. Please note that there also is a separate Technical Guide for Chapters 4 and 5 of the VTrans Policy Guide.

The purpose of developing a risk and opportunity register is to create a systematic and methodical process to identify, monitor, and react to external factors that directly or indirectly impact goals and objectives established by the CTB. The purpose of this process is not to predict the future, but to be better prepared to address the impact of external factors to achieve more desirable outcomes.

1.1 Public Involvement

Gathering and considering feedback from local and regional transportation partners and the public is an integral part of the CTB's policy development process as well as integral to the methods used to implement the CTB policies. The outlined methods may continue to evolve and improve based upon advances in technology, data collection and reporting tools. To the extent that any such improvements modify or affect the policy and process set forth in the VTrans Policy Guide, they shall be brought to the CTB for review and approval.

1.2 Known Limitations and Opportunities for Continuous Improvement

The execution of this Policy for the Development and Monitoring of the VTrans Long-term Risk & Opportunity Register relies on available research, availability of data at the desired spatial and temporal levels, and computations to ensure transparent, data-driven, and replicable methods. The following should be noted:

- Uncertainties: There are several known uncertainties related to different datasets used for the execution of the Policy for the Development and Monitoring of the VTrans Long-term Risk & Opportunity Register. These uncertainties include, but are not limited to, the following:
  - Policy uncertainty: Globally, countries are making commitments to, for example, further accelerate certain macrotrends such as the adoption of electric vehicles or decelerate other macrotrends such as increased risk from flooding. However, there are uncertainties around timeframes for implementation of and adherence to the commitments.
  - Scientific uncertainty: Impacts of mega- and macrotrends are an evolving area of scientific inquiry which influences understanding of economic, social, and ecological impacts (positive and negative) of the identified mega- and macrotrends. This evolving understanding introduces another source of uncertainty.

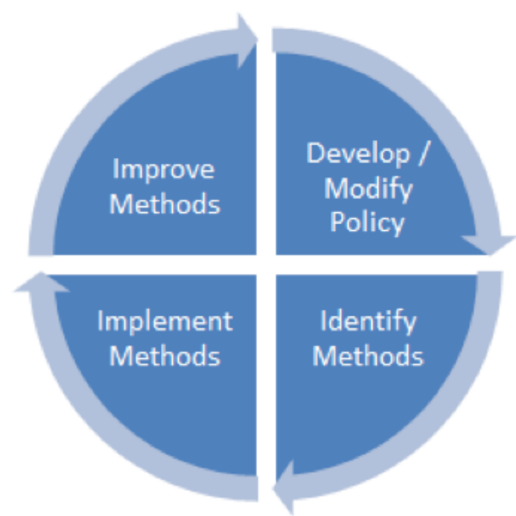
[1] Commonwealth Transportation Board, Actions to Approve the Policy for the Prioritization of the VTrans Mid-term Transportation Needs and Accept the Prioritized 2019 VTrans Mid-term Needs, March 17, 2021.

- Forecast Uncertainty: Forecasting conditions into the future holds uncertainty by nature - forecasts are rarely accurate and the further out in time a projection is, the more inaccurate it may be, due to the other uncertainties mentioned here or other random or non-random events or conditions.
- Model uncertainty: Even with a good understanding of scientific processes, it is difficult to represent them due to the data and computational limitations outlined below.

- Data: The execution of the surrogate measures estimates described in this document relies on a variety of data from academic and non-profit institutions as well federal, state, and other sources. Each of these sources relies on various methods, techniques, and technologies to develop its datasets and, therefore, has its own limitations such as:
  - Lack of applicable research: Impacts of mega- and macrotrends are a relatively new research area. While a lot of research is available, there are several research gaps or, at minimum, need for further validation of available research. For example, there is relatively little research available on state or metropolitan-wide transportation impacts of the growth of e-commerce, a VTrans Macrotrend.
  - Lack of readily usable data: There are instances in which completeness and accuracy of datasets is not sufficient to execute the steps for the development of the VTrans Long-term Risk & Opportunity Register. For example, while impacts of VTrans Macrotrends on Vehicle Miles Traveled (VMT) is estimated as part of Step 3, the estimated VMT cannot be assigned using spatial and temporal dimensions to identify impacts of VTrans Macrotrends on roadway congestion or roadway travel time reliability.
  - Confounding variables: The development of the Long-term Risk & Opportunity Register, even in the presence of very precise, readily available data, can be prone to errors due to confounding variables. For example, a VTrans Macrotrend identified in Step 1 is estimated to reduce peak-hour home-based work trips, these estimates are based on the assumptions related to the desire to telework which are influenced by several non-transportation related factors such as school drop-off for children on the way to work, etc.
- Computations: The surrogate measure estimates described in this document require synthesis, format conversions, and computations, such as those required by the following examples, that could result in inadvertent errors. In those instances, the Board-adopted Policy and the methods, processes, and techniques documented in this Technical Guide take precedence.
  - Units: Different data sources are reporting at different units of aggregations. Some are available by directional segment (e.g. VTrans Macrotrend # 1: Increase in Flooding Risk) whereas other datasets are available by area or sub-area levels (e.g. VTrans Macrotrend # 5: Growth in E-commerce).
  - Frequency of updates: Some datasets can be updated on a monthly or annual basis (e.g. VTrans Macrotrend # 3: Adoption of Electric Vehicles) while other datasets are updated once every five years approximately (e.g. sea-level rise estimations used for VTrans Mactotrend # 1: Increase in Flooding Risk).

The limitations listed above can also be seen as opportunities for continuous improvement (Figure 1). By adapting to and adjusting to these limitations, the methodology outlined in this Technical Guide can change and improve based on an evolving understanding of mega- and macrotrends as well as to reflect advances in data quality, datacollection, and reporting tools. To the extent that any such improvements modify or affect the policy, public review and CTB's approval will be sought.

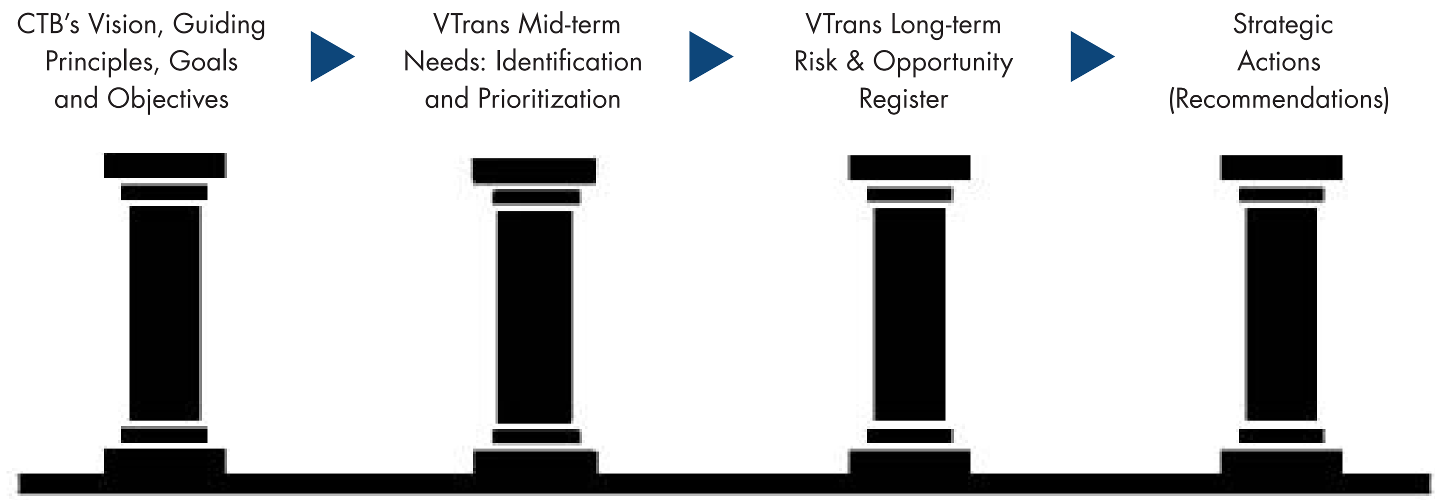
Figure 1: Opportunities for Continuous Improvement



2. INTRODUCTION TO VTRANS – VIRGINIA'S TRANSPORTATION PLAN

VTrans is the Commonwealth of Virginia's multimodal transportation plan to advance the Commonwealth Transportation Board's (CTB) vision for transportation in the Commonwealth. The CTB, with assistance from the Office of Intermodal Planning and Investment (OIPI)[1], develops VTrans to identify transportation needs which may be addressed by multimodal infrastructure projects, transportation strategies, creation of new policies, or modifications to existing policies. This Technical Guide addresses technical methods and processes related to the Policy for the Development and Monitoring of the VTrans Long-term Risk & Opportunity Register as outlined in the Chapter 6 of the VTrans Policy Guide (Figure 2).

Figure 2: Major Components of VTrans



2.1 VTrans Vision, Guiding Principles, Goals, and Objectives

The first major component of VTrans, the development of the Vision, Guiding Principles, Goals, and Objectives, forms the basis upon which the remaining three major components, the VTrans Mid-term Needs, VTrans Long-term Needs, and Strategic Actions, are developed to advance the CTB's vision. The CTB updated and adopted the VTrans Vision, Guiding Principles, Goals, and Objectives in 2020.

2.2 VTrans Planning Horizons

The CTB identifies needs for the following two planning horizons. This Technical Guide focuses on the long-term planning horizon:

- Mid-term Planning Horizon: VTrans' analysis for the mid-term planning horizon is developed to help identify some of the most pressing transportation issues that need to be addressed over the next ten years. These needs are referred to as VTrans Mid-term Needs. The needs are identified so that they can inform or guide transportation policies, strategies, and infrastructure improvements developed and implemented by the Virginia Department of Transportation (VDOT) and the Department of Rail and Public Transportation (DRPT), as well as local and regional entities.
- Long-term Planning Horizon: VTrans analysis for long-term planning identifies risks and opportunities over the next 20+ year planning period. This Technical Guide is a synthesis of technical methods and processes used to execute the CTB Policy for the Development and Monitoring of the VTrans Long-term Risk & Opportunity Register as outlined in the Chapter 6 of the VTrans Policy Guide.

[1] Office of Intermodal Planning and Investment of the Secretary of Transportation established pursuant to § 2.2-229

3. VTRANS LONG-TERM RISK & OPPORTUNITY REGISTER

The VTrans Long-term Risk & Opportunity Register is developed based on the following steps:

- Step 1: Megatrends and associated Macrotrends are identified.
- Step 2: CTB's priorities are identified based on CTB's Vision, Goals, and Objectives.[1]
- Step 3: Impact of Mega- and Macrotrends on CTB's priorities is estimated.
- Step 4: VTrans Long-term Risk & Opportunity Register is developed based on the estimated impacts on established priorities.
- Step 5: OIPI reviews and provides annual updates to the CTB for the identified risks and opportunities.

Figure 3: Steps for Development and Monitoring of VTrans Long-term Risk & Opportunity Register

Step 1: Identify Mega- and Macrotrends

Megatrends are identified as key external factors:
- Climate Change
- Technological Advancements
- Change in Consumption Patterns
- Socio-demographic Changes

Step 2: Identify Surrogates for CTB Goals

Priorities associated with CTB Goals are identified:
- Goal A: Vehicle Miles Traveled (VMT)
- Goal B: Switch to Shared Mobility
- Goal C: Safety
- Goal D: Transportation System Preservation
- Goal E: Emissions

Step 3: Estimate Impact of Macrotrends on CTB Priority Areas

A range of potential impacts of the megatrends (Step 1) on the surrogate measures (Step 2) are identified.

Step 4: Develop VTrans Long-term Risk & Opportunity Register

The VTrans Long-term Risk & Opportunity Register is developed based on feedback from policy makers and stakeholders.

Step 5: Track Macrotrends

VTrans Trend Trackers are utilized for annual reporting to the CTB.

[1] Commonwealth Transportation Board, Actions to Approve the 2019 VTrans Vision, Goals, Objectives, Guiding Principles and the 2019 Mid-term Needs Identification Methodology and Accept the 2019 Mid-term Needs, January 15, 2020

3.1. Step 1: Identify Mega- and Macrotrends

Megatrends are defined as "the great forces in societal development that will very likely affect the future in all areas over the next 10-15 years. A megatrend is also defined as "a large, social, economic, political, environmental or technological change that is slow to form. Once in place, megatrends influence a wide range of activities, processes and perceptions, both in government and in society, possibly for decades. They are the underlying forces that drive trends."[1]

A macrotrend is defined as "An emerging pattern of change likely to impact state government and require a response. Multiple macrotrends can be associated with a megatrend."[2]

Mega- and Macrotrends that are directly or indirectly significant from a transportation planning and investment perspective are identified based on literature review and are shown in Table 1 below. These are referred to as VTrans Megatrends and VTrans Macrotrends to differentiate them from other mega and macrotrends that exist.

Table 1: VTrans Mega- and Macrotrends

MEGATREND 1: CLIMATE CHANGE
Macrotrend # 1: Increase in Flooding Risk
MEGATREND 2: TECHNOLOGICAL ADVANCEMENTS
Macrotrend # 2: Adoption of Highly Autonomous Vehicles
Macrotrend # 3: Adoption of Electric Vehicles
Macrotrend # 4: Growth in Shared Mobility
MEGATREND 3: EVOLVING CONSUMPTION PATTERNS
Macrotrend # 5: Growth in E-commerce
Macrotrend # 6: Greater Automation of Goods and Services
MEGATREND 4: SOCIO-DEMOGRAPHIC CHANGES
Macrotrend # 7: Growth of Professional Service Industry
Macrotrend # 8: Increase in Workplace Flexibility
Macrotrend # 9: Growth of the 65+ Cohort
Macrotrend # 10: Population and Employment Shift

[1] European Foresight Platform

[2] Transportation Policy Task Force Suggested State Legislation Docket. 2009. California

3.1.1. VTrans Macrotrend # 1: Increase in Flooding Risk

Description: This VTrans Macrotrend refers to increase in flooding risk due to: (1) sea-level rise; (2) storm surge; and, (3) inland and riverine flooding.

Drivers: The National Oceanic and Atmospheric Administration (NOAA) describes factors affecting climate as natural and human-caused Climate Drivers.[1] According to NOAA, human-caused climate drivers include:

- emissions of heat-trapping gases (also known as greenhouse gases)
- changes in land use that make land reflect more or less sunlight energy

Significance: According to the Fourth National Climate Assessment,[2] "the number and cost of weather and climate disasters are increasing in the United States due to a combination of increased exposure (i.e., more assets at risk), vulnerability (i.e., how much damage a hazard of given intensity—wind speed, or flood depth, for example—causes at a location), and the fact that climate change is increasing the frequency of some types of extremes that lead to billion-dollar disasters."

[1] National Oceanic and Atmospheric Administration (NOAA). Climate Forcing. Accessed on July 8, 2021.

[2] U.S. Global Change Research Program. Fourth National Climate Assessment (NCA4).

Data Sources: Data sources for calculating flooding risk or measuring transportation system vulnerability to flooding are listed in Table 2 by hazard type:

Table 2: Data Sources by Scenario for Estimating Risk from Flooding Events

Hazard	Data Source of Estimated Hazard	Scenario 1	Scenario 2	Scenario 3
Sea Level Rise	Virginia Institute of Marine Sciences (VIMS)	Intermediate sea level rise scenario (Year 2040)	Intermediate-High sea level rise scenario (Year 2040)	Extreme sea level rise scenario (Year 2040)
Storm Surge	National Hurricane Center (NHC)	Category 2 hurricane storm surge	Category 3 hurricane storm surge	Category 4 hurricane storm surge
Inland/Riverine Flooding	Federal Emergency Management Agency (FEMA) VDOT	100-year flood zone AND Historical Weather-Related Damages or Closures	500-yr flood zone AND Historical Weather-Related Damages or Closures	FEMA 500-yr flood zone with varying width buffer (10-200ft) based on floodplain width AND Historical Weather-Related Damages or Closures (Appendix 1-F)

Source of Methodology: The methodology is based on Federal Highway Administration's FHWA Vulnerability Assessment Scoring Tool (VAST) for each of the three scenarios outlined in Table 2. This approach uses data on asset location and other key attributes as indicators of each of the three components of vulnerability: (1) Exposure; (2) Sensitivity; and, (3) Adaptive Capacity.

Calculations: Please refer to Appendix 1: VTrans Macrotrend # 1: Increase in Flooding Risk for a detailed description of the methods and calculations. This memorandum also outlines scope, limitations, and as the intended utilization of the calculations.

3.1.2. VTrans Macrotrend # 2: Adoption of Highly Autonomous Vehicles

Description: This Macrotrend refers to full or partial automation of driving activities in personal and commercial vehicles. This analysis relies on automation categorization developed by Society of Automotive Engineers (SAE). Please refer to the definitions in Section 1 of this document.

Significance: Growth in the number of highly autonomous vehicles, referred to as AVs, in the fleet will potentially impact roadways' effective traffic-carrying capacity, roadway safety, and operation costs of vehicles, and may also impact travel demand.

Drivers:

- Advancement of vehicle sensing and information processing technologies for automation[1]
- Industry-wide push and investments towards development of automated vehicles[2]
- Consumer preferences for safety and openness to vehicle technology[3]

Data Sources:

- Adoption Curves for personal AVs: Bansal and Kockelman[4]
- Adoption Curves for commercial AV Technology: Mishra, Golias, et al.[5]
- Commercial Vehicles and Firms in Virginia: FMCSA[6]

[1] Reuters, Self-Driving Costs could drop 90% by 2025

[2] Forbes, Driverless Cars Gain Speed despite Global Slowdown

[3] AAA, Today's Vehicle Technology Must Walk So Self-Driving Cars can Run

[4] Bansal, P., Kockelman, K. (2017). Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies.

[5] Mishra, Sabya, Mihalis Golias, and Evangelos Kaisar (2019). "Modeling Adoption of Autonomous Vehicle Technologies by Freight Organizations." College Park, MD: Freight Mobility Research Institute.

[6] FMCSA, Motor Carrier Census System. Accessed in February 1, 2021

Calculations:

Estimate the market penetration of personal/passenger AVs for years 2020 to 2045.

1. For personal vehicles, utilize personal/passenger AV adoption for low, medium, and high scenarios using adoption rates developed by Bansal & Kockelman (2017).[1]

Estimate the market penetration of commercial AVs for years 2020 to 2045.

2. Obtain data[2] related to motor carriers in Virginia as of February 1, 2021.
3. Utilize the fields 'Number of Power Units' (equivalent of vehicles) and 'Number of Drivers' to conduct a k-means clustering[3] to categorize 18,564 motor carriers as 'small', 'medium', or 'large'.
4. Use market studies/reports to estimate a commercial readiness year for the technology. For each technology, associate an adoption scenario type (baseline, conservative, or optimistic) also based on market studies and reports. If the technology has already been introduced, its actual introduction year is used. The results of this market analysis are listed in Table 3 by technology and adoption scenario type.

Table 3: Estimated Commercial Readiness Year for Vehicle Technologies

Commercial Vehicle Technology	Commercial Readiness Year	Adoption Curve Type
Platooning	2025	Conservative
Predictive Cruise	2016	Baseline
Adaptive Cruise	2019	Baseline
Automated Manual Transmission	2006	Optimistic
Level 4 Automation	2030	Conservative

5. For each automation technology, generate an adoption curve for each motor carrier size (small, medium, and large) and sum them. This results in one adoption curve for the state of Virginia for each automation technology. The adoption curves are generated using parameters based on the motor carrier size and the adoption scenario type, as defined in Mishra et al. (2019).[4]
6. Use the market readiness year from Step # 4 and the adoption curves generated in Step # 5 to estimate the market penetration rate of each commercial vehicle automation feature in 2045. Results are shown in Table 3 below.
7. Use the readiness year from calculation Step # 4 and the adoption curves used in calculation Step # 5 to estimate the market penetration rates each of commercial vehicle automation features. Results are shown in Table 3 below.

[1] Bansal, P., Kockelman, K. (2017). Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies. Tables 6, 7, and 8.

[2] FMCSA, Motor Carrier Census System

[3] K-means Clustering

[4] Mishra, Sabya, Mihalis Golias, and Evangelos Kaisar. Modeling Adoption of Autonomous Vehicle Technologies by Freight Organizations. College Park, MD: Freight Mobility Research Institute, 1/19

Step 1: Macrotrend # 3: Adoption of Highly Autonomous Vehicles Output

Table 4: Estimated Market Penetration of Vehicle Automation in Year 2045 by Vehicle Automation Levels

Vehicle Automation Levels	Estimated Market Penetration of Vehicle Automation Levels		
	Low Estimate	Medium Estimate	High Estimate
Passenger Vehicles			
Level 1 and 2 (Lane Centering)	41%	60%	98%
Level 1 and 2 (Adaptive Cruise Control)	47%	68%	98%
Level 3	9%	8%	3%
Level 4	25%	43%	87%
Commercial Vehicles			
Level 0 - Automated Manual Transmission		80%	
Level 1- Adaptive Cruise Control		40%	
Level 1 and 2 Platooning		18%	
Level 4		12%	

Assumptions

- Market penetration rates are based on considering the willingness to pay for one or more types of automated technologies in use. In reality, vehicle automation is expected to include many different types of automated technologies especially when considering Levels 1 to 3.
- Level 3 technologies are assumed to be a transition stage technology and hence have low levels of penetration in higher-end estimates of market penetration since they are assumed to have been replaced by Level 4 vehicles.
- Assume that the V2X connectivity is factored into the willingness to pay for level 4 technology and no separate estimation for connected vehicles are developed.

3.1.3. VTrans Macrotrend # 3: Adoption of Electric Vehicles

Description: Electric Vehicles (EVs) use electric motors powered by batteries, rather than internal combustion engines powered by petroleum-based fuels. This trend estimates the adoption of Electric Vehicles (EVs) in the Commonwealth of Virginia in the year 2045.

Significance: EVs are a small but growing share of the automobile market. As their price decreases, demand for EVs as well as for supportive infrastructure will increase. EVs promise higher efficiencies and lower tailpipe emissions, enabling greenhouse gas (GHG) reduction initiatives to focus on clean power generation. They also may require additional investment in infrastructure, such as electric vehicle chargers to support their operations.

Drivers:

- Technological advancements in EV battery technology
- Increased vehicle availability of EVs[1]
- Decreasing manufacturing costs[2]
- Growth in national charging infrastructure[3]
- Public policy drivers to reduce GHG emissions, for example, Corporate Average Fuel Economy Standards[4]

Data Sources:

- Market penetration of EVs from 2019-2045: Virginia Energy Policy Simulator
- Reduction in CO2e emissions due to EVs: Virginia Energy Policy Simulator

[1] Deloitte (2020). Electric Vehicles: Setting a Course for 2030.

[2] Baik, Y., Hensley, R., Hertzke, P., and Knupfer, S. (2019). Making Electric Vehicles Profitable. McKinsey & Company.

[3] Brown, A., Lommele, S., Schayowitz, A., and Klotz, E. (2020). Electric Vehicle Charging Infrastructure Trends from the Alternative Fueling Station Locator: First Quarter 2020. Technical Report. National Renewable Energy Laboratory, U.S. Department of Energy. Report number NREL/TP-5400-77508.

[4] Corporate Average Fuel Economy (CAFE) Standards | US Department of Transportation

Calculations:

1. Estimate the market penetration of EVs from 2019-2045 based on three scenarios: Business as Usual, National 1.5 degree and Accelerated Electrification, from the Virginia Energy Policy Simulator (EPS) Tool.[1,2]
2. Based on the scenario used for market penetration of EVs, determine the potential reduction in carbon dioxide equivalent greenhouse gas emissions (CO2e) emissions due to EVs considering Virginia's current electricity generation sources. Using the same tool, select emissions in CO2e due to transportation for each of the three scenarios, review the effect of EVs on the CO2e emissions for Virginia. Emissions of relevant pollutants that will be reduced due to vehicle electrification alone are assumed to follow the trends in vehicle CO2e emissions, which are reported in the Virginia Energy Policy Simulator. This accounts for the fact that electricity generation can generate air pollutants, and that the amount of mix of air pollutants depends on the energy sources. "Business as Usual" corresponds with the low scenario, "Accelerated Electrification" corresponds with the high scenario The percentage reduction of CO2e emissions between 2020 and 2045 is calculated for the low and high scenarios, and the percentage reduction for the medium scenario is the average of the low and the high scenarios.[3]

Table 5: Step 1 Outputs

Electric Vehicle Type	Estimated Market Penetration in 2045		
	Business as Usual	National 1.5 Degree	Accelerated Electrification
Cars and SUV	40%	98%	100%
Buses	23%	81%	92%
Light-Duty Trucks	41%	71%	100%
Medium and Heavy Duty Trucks	1%	48%	41%
Motorbikes	38%	92%	38%
Reduction in CO2e Emissions	39%	84%	85%

Assumptions

- Adoption of EVs and Reduction in emissions was calculated using the Virginia Energy Policy Simulator.[4] The assumptions for Virginia Energy Policy Simulator can be found in the model documentation.

[1] "Virginia Energy Policy Simulator." Virginia. Accessed April 08, 2021.

[2] Assumptions for the EPS tool can be found here. Energy Innovations (n.d.). Virginia Energy Policy Simulator (EPS) Summary Documentation.

[3] Assumptions of the Virginia Energy Policy Simulator related to electrification are available here: *Energy Policy Solutions (n.d.). Virginia Energy Policy Simulator (EPS) Summary Documentation.*

[4] Virginia Energy Policy Simulator

3.1.4. VTrans Macrotrend # 4: Growth in Shared Mobility

Description: Shared mobility services such as micromobility services (bikesharing, scooter sharing) and ridesourcing (e.g., transportation network companies) have seen recent explosive growth in scope and services offered.[1] This trend will show the number of trips that could be accommodated by micromobility and ridesourcing in 2045.

Drivers:

- Growth in Broadband, and high prevalence and increasing capabilities of mobile communication devices[2]
- Increase in number of workers interested in work hour flexibility or willing to work in the 'gig' economy[3]

Significance: While shared mobility services are a small portion of the trips statewide, in certain geographies they play an important role in providing non-auto travel options.[4,5] Shared mobility has the potential to change travel costs and convenience, and to affect the amount traveled and the modes selected.

Data Sources:

- Vehicle Trips: StreetLight Data[6]
- Shared Mobility Growth Rates: Uber and Lyft S-1 Filings[7,8] and NACTO[9]
- Micromobilty local trip rates: Pilot program reports[10]

[1] Price, Jeff, Blackshear, Danielle Blount, Jr., Wesley and Sandt, Laura. Micromobility: A Travel Mode Innovation. US DOT FHWA Public Roads, Vol. 85 Issue 1, Spring 2021.

[2] Pew Research Center, Mobile Fact Sheet, 2021

[3] Brookings Instituion, Tracking the gig economy: New numbers, 2016

[4] Jin, S., Kong, H., Wu, R., Sui, D. (2018). *Ridesourcing, the Sharing Economy, and the Future of Cities.*

[5] Heineke, K., Kloss, B., Scurtu, D., Weig, F. (2019). *Micromobility's 15,000-Mile Checkup.* McKinsey & Company.

[6] Transportation Analytics On Demand | StreetLight Data

[7] Form S-1 Registration Statement, Uber Technologies, Inc. S-1 (sec.gov)

[8] Form S-1 Registration Statement, Lyft, Inc., S-1 (sec.gov)

[9] NACTO. "Shared Micromobility in the US: 2019," 2020.

[10] Portland, Arlington, Santa Monica, Kansas City, Chicago.

- Households by county: US Census Bureau (2019): American Community Survey[1]
- Daily vehicle trips per household FHWA (2017): National Household Travel Survey[2]
- Ridesource share of local VMT: Fehr & Peers[3]
- Micromobility distribution of trip lengths: Zou et al.[4]
- Percent of trips of different modes replaced by micromobility: McQueen et al.[5]
- Ridesource/taxi distribution of trip lengths: National Household Travel Survey[6]

Calculations:

Estimate possible micromobility and ridesource trip market for Virginia.

1. Develop a maximum trip length market for micromobility and ridesourcing services. Estimate the share of micromobility trips and ridesource trips by length as provided by Zou et al.[7] and Oak Ridge National Laboratory's (ORNL) National Household Travel Survey[8] (NHTS) respectively. Results are shown below in Tables 4 and 5, column (b).
2. Estimate base year (2019) overall daily auto trips and daily auto VMT by average trip starts in Virginia by county and by trip length categories established in calculation step # 1 above.
   (Daily Auto VMT) = number of daily auto trips × trip distance midpoint

Where:

- *number of daily auto trips 2019*[9]
- *trip distance midpoint*[10]

3. Estimate trips and VMT that could possibly be completed by micromobility or ridesourcing in future year (2045). For maximum switchable VMT, it is assumed that all counties can support these systems. Inflate daily trips and VMT by population estimation to develop daily estimates for 2045. Trips and VMT in each county increase proportionally to an extrapolated population estimation for 2045.
   Trips (2045) = number of daily auto trips 2019 × county specific population growth rate, 2020-2045

   Where:
   - *Trips (2045)* is the estimated number of trips by trip length category in 2045
   - *number of daily auto trips 2019*[11]
   - *county specific population growth rate*[12]

[1] U.S. Census Bureau (2019). 2019 American Community Survey Five-year estimates.

[2] U.S. Department of Transportation (2017). *Summary of Travel Trends: 2017 National Household Travel Survey.* FHWA-PL-18-01.

[3] Fehr & Peers (2019). Estimated TNC Share of VMT in Six US Metropolitan Regions Memorandum

[4] Zou, Zhenpeng, Hannah Younes, Sevgi Erdogan, and Jiahui Wu. "Exploratory Analysis of Real-Time E-Scooter Trip Data in Washington, D.C." Transportation Research Record: Journal of the Transportation Research Board 2674, no. 8 (August 2020): 285–99.

[5] McQueen, Michael, Gabriella Abou-Zeid, John MacArthur, and Kelly Clifton. "Transportation Transformation: Is Micromobility Making a Macro Impact on Sustainability?" Journal of Planning Literature, November 15, 2020, 088541222097269.

[6] Federal Highway Administration. (2017). 2017 National Household Travel Survey, U.S. Department of Transportation, Washington, DC.

[7] Zou, Zhenpeng, Hannah Younes, Sevgi Erdogan, and Jiahui Wu. "Exploratory Analysis of Real-Time E-Scooter Trip Data in Washington, D.C." *Transportation Research Record: Journal of the Transportation Research Board* 2674, no. 8 (August 2020): 285–99.

[8] Federal Highway Administration. (2017). 2017 National Household Travel Survey, U.S. Department of Transportation, Washington, DC.

[9] Trip length categories are based on Zou et al.

[10] Streetlight data

[11] Trip length categories are based on Zou et al.

[12] Demographics Research Group of the Weldon Cooper Center for Public Service at University of Virginia.

4. Utilize the output of calculation step # 1 to develop trip distribution share by trip length category for micromobility trips and ridesource trips. Results are shown in column (c) in Table 4 and Table 5 below respectively.

Table 6: Share of Micromobility Trips by Length[1]

Trip Length Categories (Miles) (a)	Estimated VA Micromobility Trips in 2045 (b)	Share of Trips (c)
0 – 1	73,000	64%
1 – 2	29,000	25%
2 – 5	11,750	10%
Total		100%

Table 7: Share of Ridesource Trips by Length[2]

Trip Length Categories (Miles) (a)	Estimated VA Ridesource Trips in 2045 (b)	Share of Trips (c)
0 - 1	173,000	10%
1 - 2	347,000	19%
2 - 5	654,000	36%
5 - 10	380,000	21%
10 - 20	200,000	11%
20 - 30	61,000	3%
Total		100%

5. Estimate the maximum amount of trips and VMT that could be completed via micromobility and ridesourcing services. This estimate is created by assuming 100% conversion from SOV to micromobility or ridesourcing of trips that fit the trip length categories of shared mobility services.
6. Estimate potential additional market, for micromobility or ridesourcing based on the difference between the current market estimate and the overall maximum market estimate established in calculation step # 5.
   a. Estimate how much of the maximum micromobility and ridesourcing market is currently being served by these services in 2020 – call this the base discount factor. Calculate discount factors for micromobility pilots in Portland, OR[3]; Arlington, VA[4]; Santa Monica, CA[5]; Kansas City, MO[6]; and Chicago, IL.[7] The pilots provide a data point on the trips per day which is then divided by estimated daily vehicle trips in the jurisdiction, as illustrated in Table 7 below. Ridesourcing discount factors are based on a Fehr and Peers report.[8]

[1] Zou, Zhenpeng, Hannah Younes, Sevgi Erdogan, and Jiahui Wu. "Exploratory Analysis of Real-Time E-Scooter Trip Data in Washington, D.C." Transportation Research Record: Journal of the Transportation Research Board 2674, no. 8 (August 2020): 285–99.

[2] Federal Highway Administration. (2017). 2017 National Household Travel Survey, U.S. Department of Transportation, Washington, DC.

[3] Portland Bureau of Transportation (2018). E-Scooter Findings Report.

[4] Arlington County, VA (2019). Arlington County Shared Mobility Devices (SMD) Pilot Evaluation Report.

[5] City of Santa Monica (2019). Shared Mobility Pilot Program Summary Report.

[6] Kansas City (n.d.). KCMO Micromobility Pilot Program First-Year Analysis.

[7] City of Chicago (2021). 2020 E-Scooter Pilot Evaluation.

[8] Fehr & Peers (2019). Estimated TNC Share of VMT in Six US Metropolitan Regions Memorandum.

Table 8: Micromobility Discount Factor Calculation

City	Number of Days (a)	Micro-mobility Trips (b)	Micro-mobility Trips per Day (c=b/a)	Annual Micro-mobility Trips (d=c*365)	Number of households[1] (e)	Average Daily Vehicle Trips per Household[2] (f)	Total annual vehicle trips (g=e*f)	Annual Micro-mobility Trips as Percent of Regional Vehicle Trips (h=d/g)
Portland, OR	120	70,038	584	213,032	326,229	5.11	608,466,019	0.035%
Arlington, VA	243	453,690	1,867	681,469	107,032		199,630,735	0.341%
Santa Monica, CA	335	2,673,819	7,982	2,913,265	3,316,795		6,186,320,194	0.047%
Kansas City, MO	397	374,000	942	343,854	286,601		534,553,855	0.064%
Chicago, IL	122	540,005	4,426	1,615,589	19,72,108		3,678,277,236	0.044%
Average (Discount Factor for Micromobility):								0.106%

7. Develop compound annual growth rates for micromobility and ridesourcing trips based on market research. The assumed compounding annual growth rate is based on growth rates able to be determined from trip rates found in Lyft/Uber S-1 SEC filings and the National Association of City Transportation Officials (NACTO) 2019 micromobility report. Growth rates are assumed to decrease over time as systems mature, and will provide the stated compound annual growth rate (CAGR). Assumed CAGRs are:

   Micromobilty: 20% CAGR (from 2020-2035), 5% (2035-2045)
   Ridesourcing: 15% CAGR (from 2020-2035), 5% (2035-2045)

8. Apply compound annual growth rates to baseline discount factors to illustrate growth in services from 2020-2045 and estimate 2045 discount factors. The total trips that are estimated to replace vehicle trips are a product of the base total trips discount factor (based on region-wide estimated total vehicle trips data), assumed compound annual growth in percent of region-wide vehicle trips, and the distribution of trips by trip distance buckets.
   2045 discount factor = 2020 base discounty factor (1 + CAGR)^t

   Where:
   - 2020 base discount factor as established in calculation step # 6.
   - CAGR is the compound annual growth rate established in calculation step # 7.
   - t is the number of years (25) to apply CAGR.

9. Estimate the amount of automobile VMT replaced by (or switched to) micromobility and ridesourcing in 2045 by Virginia locality, based on the results from calculation step # 8.
   $\text{automobile VMT replaced} = \sum_{i=\text{trip lenth category}} \text{locality automobile trips}_i \times \text{2045 discount factor} \times r \times m_i$
   - *automobile VMT replaced* is the total VMT by locality
   - *2045 discount factor* is from calculation step # 8.
   - *r* is the percent of trips of that mode replacing auto.[3]
   - *m* is the trip length category midpoint determined in calculation step # 1.

[1] U.S. Census Bureau (2019). 2019 American Community Survey.

[2] U.S. Department of Transportation (2017). Summary of Travel Trends: 2017 National Household Travel Survey. FHWA-PL-18-01.

[3] Assumed as 30%. McQueen, Michael, Gabriella Abou-Zeid, John MacArthur, and Kelly Clifton. "Transportation Transformation: Is Micromobility Making a Macro Impact on Sustainability?" Journal of Planning Literature, November 15, 2020, 088541222097269. For ridesourcing/transportation network companies (TNCs), this replacement is assumed as 40% based on Schaller Consulting.

3.1.5. VTrans Macrotrend # 5: Growth in E-commerce

Description: E- commerce is the process of purchasing products on the internet which are then delivered directly to a home or business.

Drivers:

- Customer convenience[1]
- Consumer willingness to pay for delivery shipping services[2]
- Automation of warehousing

Significance: Growth in e-commerce is expected to have impacts on transportation and the economy, including changing product sourcing and operating costs, product availabilities, changing delivery methods, and freight movements.

Data Sources:

- Historical wholesale trade or business-to-business (B2B) e-commerce and total sales for North American Industry Classification System (NAICS) industry: US Census, Annual Wholesale Trade Survey (AWTS)[3]
- US Monthly Retail Trade Survey (MRTS): US Census[4]
- US Quarterly Retail E-Commerce and Total Sales: US Census[5]
- Virginia Industry Mix: Multiple sources[6]
- Historical retail/business-to-consumer (B2C) e-commerce and total sales for NAICS industry

[1] National Retail Federation, Consumer View Winter 2020.

[2] Businesswire, New Research Finds 65% of Consumers Willing to Pay More for Faster Deliveries, June 16 2021.

[3] US Census Annual Report for Wholesale Trade, 2019 (last accessed on April 8, 2021)

[4] US Census Quarterly E-Commerce Report Historical Data (last accessed on April 8, 2021)

[5] US Census Monthly Retail Trade Survey Historical Data (last accessed on April 8, 2021)

[6] US Census, Monthly Retail Trade Survey, 1992-2020 Retail and Food Services Sales, as on December 16, 2020; US Census, Quarterly E-Commerce Report, 2018 Q1 to 2020 Q3 Supplemental Quarterly E-Commerce Tables as on November 19, 2020; US online retail forecast by FTI Consulting, 2019; Industry Articles; Virginia Department of Taxation via Weldon Cooper Center for Public Service, Historical Virginia State Annual and Quarterly Taxable Sales by NAICS 3-digit Industry, Year 2018, Year 2019, Year 2020 Q1-Q3; and Forecast and Market Penetration by Industry Assumptions.

- US Output (GDP) by Industry data: US Bureau of Economic Analysis[1]
- Virginia Annual taxable wholesale trade sales data: Virginia Department of Taxation via Weldon Cooper Center[2]
- Virginia Employment forecasts: Woods & Poole[3]
- 2020-2050 vehicle stock and fuel efficiency: US Energy Information Agency[4]
- Current local gas prices: AAA[5]
- Last-mile delivery and fulfillment center costs percent of sales: Dubai Multi Commodities Centre[6]

Calculations:

Estimate E-commerce Market Penetration, as share of Total Dollar Value of Sales, for the Wholesale/ Business-to-Business (B2B) market, for years 2019 and 2045

1. Estimate base year (2019) B2B e-commerce market penetration rates for the US by three-digit NAICS industry.
   $Base\ E\text{-}com\ Sales\ \%_i^{US} = Base\ E\text{-}Com\ Sales_i^{US} / Base\ Total\ Sales_i^{US}$

   Where:
   - $Base\ E\text{-}com\ Sales_i^{US}$ is the US's 2018 wholesale trade or B2B e-commerce sales for NAICS industry *i* gathered from US Census' US Annual Merchant Wholesaler data[7]
   - $Base\ Total\ Sales_i^{US}$ is the US's 2018 wholesale trade or B2B total sales for NAICS industry *i* gathered from US Census' US Annual Merchant Wholesaler data[8]
   - $Base\ Total\ Sales_i^{VA}$ is Virginia's 2018 Q1-2020 Q3 wholesale trade or B2B total taxable sales for NAICS industry *i* gathered from Virginia Department of Taxation's annual taxable wholesale trade or B2B sales data published on Weldon Cooper Center website[9]
   - *i* is the index for NAICS industries 423 (Durable Goods) and 424 (Nondurable Goods)

2. Apply the US e-commerce penetration rates by NAICS three-digit industry found in calculation step # 1 to estimate the base year (2019) e-commerce wholesale market penetration rates by industry in Virginia.
   $Base\ E\text{-}com\ Sales\ \%^{VA} = \sum_i Base\ E\text{-}com\ Sales\ \%_i^{US} \times Base\ Total\ Sales_i^{VA}$

   Where:
   - $Base\ E\text{-}com\ Sales\ \%^{VA}$ is the estimated Virginia's 2019 wholesale trade or B2B e-commerce share of total sales for NAICS industry *i*
   - $Base\ E\text{-}com\ Sales\ \%^{US}$ is the estimated US's 2018 wholesale trade or B2B e-commerce share of total sales for NAICS industry *i*

3. Develop future year (2045) estimations for B2B e-commerce market share[10] for NAICS industries 423 (Durable Goods) and 424 (Nondurable Goods). Use historical (2010-2018) US B2B e-commerce shares of total sales gathered from US Census' US Annual Merchant Wholesaler data. The national trendline forecasts for e-commerce share of total sales in NAICS industries 423 and 424 were adopted for Virginia.

[1] US Bureau of Economic Analysis, Integrated Industry-Level Production Account (KLEMS); GDP-by-industry tables; GDP & Personal Income tables (last accessed on April 8, 2021)

[2] Virginia Department of Taxation via Weldon Cooper Center for Public Service, Historical Virginia State Annual and Quarterly Taxable Sales by NAICS 3-digit Industry, Year 2018, Year 2019, Year 2020 Q1- (last accessed on April 8, 2021)

[3] Provided by the Virginia Transportation Research Council (VTRC)

[4] US Energy Information Agency, Annual Energy Outlook tables (last accessed on April 8, 2021)

[5] American Automobile Association, Virginia Average Gas Prices, (last accessed on April 8, 2021)

[6] DMCC (Dubai Multi Commodities Centre). 2016. "The Future of Trade." DMCC, Dubai, and Future Agenda. last accessed on April 8, 2021.

[7] US Census Annual Report for Wholesale Trade, 2019 (last accessed on April 8, 2021)

[8] US Census Annual Report for Wholesale Trade, 2019 (last accessed on April 8, 2021)

[9] Virginia Department of Taxation via Weldon Cooper Center for Public Service, Historical Virginia State Annual and Quarterly Taxable Sales by NAICS 3-digit Industry (last accessed on April 8, 2021)

[10] MS Excel trendline function - third degree polynomial function as follows was fitted using 2010-2019 data and yields R-square value of 0.99:
-0.0000113×x3+0.0005558×x2+ 0.002322××+0.0416073, where x = year minus 2009

For NAICS industry 423: *E-com Sales % in year* $X^{US} = 0.0986 \times \ln(X-2002) + 0.1337$; $R^2=0.85$

For NAICS industry 424: *E-com Sales % in year* $X^{US} = 0.1498 \times \ln(X-2002) + 0.0679$; $R^2=0.78$

Where:

- *E-com Sales % in year* X^{US} *is the estimated US B2B e-commerce share of total sales in year X for a given NAICS industry*

4. Develop a low and high scenario by subtracting and adding 5 percentage points to the 2045 values, respectively.
5. Use a weighted average of NAICS industry categories to develop low, medium and high scenarios for wholesale e-commerce 2045 market share by three-digit industry code.

Estimate E-commerce Market Penetration, as share of Total Dollar Value of Sales, for the Retail/Business-to-Consumer (B2C) market, for years 2019 and 2045

6. Estimate base year (2019) B2C e-commerce market penetration rates for the US by three-digit NAICS industry.
   Base E-com Sales $\%_i^{US}$ = *Base E-Com* $Sales_i^{US}$/*Base Total* $Sales_i^{US}$

   Where:

   - *Base E-Com* $Sales_i^{US}$ is the US's 2018 Q1-2020 Q3 retail trade or B2C e-commerce sales for NAICS industry *i* gathered from US Census' Quarterly E-Commerce Report, 2018 Q1 to 2020 Q3 Supplemental Quarterly E-Commerce Tables as of November 19, 2020[1]
   - *Base Total* $Sales_i^{US}$ is the US's 2018 Q1-2020 Q3 retail trade or B2C total sales for NAICS industry *i* gathered from US Census' Monthly Retail Trade Survey, 1992-2020 Retail and Food Services Sales, as of December 16, 2020[2]

7. Apply the US e-commerce penetration rates by NAICS industry found in Calculation Step 6 to estimate the base year (2019) e-commerce retail market penetration rates by industry in Virginia.
   Base E-com Sales $\%^{VA} = \sum_i$ *Base E-Com Sales* $\%_i^{US} \times$ *Base Total Sales* $_i^{VA}$

   Where:

   - *Base E-com Sales* $\%^{VA}$ is Virginia's estimated 2019 B2C e-commerce share of total sales
   - *Base E-Com Sales* $\%_i^{US}$ is the US's estimated 2018 Q1-2020 Q3 B2C e-commerce share of total sales for NAICS industry *i* determined in calculation step # 1
   - *Base Total Sales* $_i^{VA}$ is Virginia's 2018 Q1-2020 Q3 B2C total taxable sales for NAICS industry *i* gathered from Virginia Department of Taxation's annual taxable B2C sales data published on Weldon Cooper Center website[3]
   - *i* is the index for NAICS industries 441-448 and 451-454

8. Develop future year (2045) Estimates for Retail/Business-to-Consumer (B2C) e-commerce market share[4] using historical (2010-2018) US B2C e-commerce shares of total sales gathered from the US Census US Annual Merchant Wholesaler data.
   E-com Sales % in year $X^{US} = -1.10 \times 10^{-5} \times (X\text{-}2009)^3 + 5.5\times10^{-4} * (X\text{-}2009)^2 + 2.3 \times 10^{-3} \times (X\text{-}2009) + 4.2\times10^{-2}$; $R^2=0.99$

   Where:

   - *E-com Sales % in year* X^{US} is the US' estimated B2C e-commerce share of total sales in year X for a given NAICS industry

   The estimated 2045 national forecast B2C e-commerce share of 33 percent based on the above equation is used as a control check on the total market size of B2C e-commerce estimated for Virginia. Due to differences in industrial mix at national and state levels, the estimated shares may differ at these geographical levels.

[1] US Census Quarterly E-Commerce Report Historical Data (last accessed on April 8, 2021)

[2] US Census Monthly Retail Trade Survey Historical Data (last accessed on April 8, 2021)

[3] Virginia Department of Taxation via Weldon Cooper Center for Public Service, Historical Virginia State Annual and Quarterly Taxable Sales by NAICS 3-digit Industry, (last accessed on April 8, 2021)

[4] MS Excel trendline function - A third degree polynomial function as follows was fitted using 2010-2019 data and yields R-square value of 0.99: -0.0000113×x3+0.0005558×x2+ 0.002322×x+0.0416073, where x = year minus 2009

9. Through a study of research articles gathered on each 3-digit NAICS industry, 2045 medium scenario (most likely) assumptions are made on B2C e-commerce shares. These are upward adjustments to the 2019 retail trade or B2C e-commerce shares based on the NAICS industry mix in Virginia.[1]
   A range of +/-5 percent by industry is assumed to represent the 2045 low and high scenarios.
   Use a weighted average of NAICS industry categories to develop low, medium and high scenarios for B2C e-commerce 2045 market share. The weights used for the 3-digit NAICS industries in 2019, that is $\textit{Base Total Sales } \%_i^{VA}$, to estimate the retail trade or B2C sector level e-commerce share are also used in 2045.

Estimate employment changes (full time equivalent) due to e-commerce for the Wholesale/B2B market at the Metropolitan Statistical Area (MSA) level for years 2019 and 2045

10. Estimate base year (2019) employment in industries related to wholesale trade sectors for Virginia and MSAs/rural areas. Use 2019 Virginia Employment by 3-digit NAICS industry for statewide and 2019 regional distribution of employment among Virginia's MSAs and Rural Areas by 2-digit NAICS Industry for MSAs/rural areas. Define MSAs by size:
    - Large MSAs: Richmond, Virginia Beach-Norfolk-Newport News and Northern Virginia
    - Medium MSAs: Charlottesville, Lynchburg, and Roanoke
    - Rest of State (Small MSAs + Rural Areas)

    $$\textit{Base E-Com Emp}_i^{Region} = \textit{Base Emp}_i^{VA} \times \textit{Base E-Com Sales } \%_i^{US} \times \textit{Base Emp } \%^{Region}$$

    Where:
    - $\textit{Base E-Com Emp}_i^{Region}$ is the estimated regional (Virginia's MSAs and Rural Areas) 2019 B2B e-commerce employment by NAICS industry *i*
    - $\textit{Base Emp}_i^{VA}$ is Virginia's 2019 Quarter 4 Month 3 B2B sector employment by NAICS industry *i* from US BLS data[2]
    - $\textit{Base E-Com Sales } \%_i^{US}$ is an input to calculation step # 7
    - $\textit{Base Emp } \%^{Region}$ is the regional 2019 employment share of Virginia's total employment in B2B sector from US BLS data[3]
    - *i* is the index for NAICS industries 423 (Durable Goods) and 424 (Nondurable Goods)

11. Estimate future year (2045) employment in industries related to wholesale trade sector for Virginia and MSAs/Rural Areas by using the 2019 estimate determined in calculation step # 10 and applying a growth factor.
    $$\textit{Future E-Com Emp}_i^{Region} = \textit{Emp GF}^{VA} \times \textit{Base E-Com Emp}_i^{Region}$$

Where:
- *E-Com Emp* is the estimated regional 2045 wholesale/B2B e-commerce employment by NAICS industry
- *Emp GF* is the 2019 to 2045 employment growth factor in wholesale/B2B sector from Woods and Poole 2017 data and 2045 forecast for Virginia's employment[4]

Estimate changes in output (in 2012 chained dollars[5] per hour) due to e-commerce for the Wholesale/Business-to-Business (B2B) market at the MSA level, for years 2019 and 2045.

[1] US Census, Monthly Retail Trade Survey, 1992-2020 Retail and Food Services Sales, as on December 16, 2020; US Census, Quarterly E-Commerce Report, 2018 Q1 to 2020 Q3 Supplemental Quarterly E-Commerce Tables as on November 19, 2020; US online retail forecast by FTI Consulting, 2019; Industry Articles; Virginia Department of Taxation via Weldon Cooper Center for Public Service, Historical Virginia State Annual and Quarterly Taxable Sales by NAICS 3-digit Industry, Year 2018, Year 2019, Year 2020 Q1-Q3; and Forecast and Market Penetration by Industry Assumptions.

[2] US Bureau of Labor Statistics, Occupational Employment and Wage Statistics (last accessed on April 8, 2021)

[3] US Bureau of Labor Statstics, State and Metro Area Employment, Hours, & Earnings (last accessed on April 8, 2021)

[4] Provided by the Virginia Transportation Research Council (VTRC)

[5] According to the U.S. Bureau of Economic Analysis, "chain-type estimates provide the best available method for comparing the level of a given series at two points in time. Chained-dollar estimates are obtained by multiplying the chain-type quantity index for an aggregate by its value in current dollars in the reference year (currently 2012) and dividing by 100." Source: U.S. Bureau of Economic Analysis. National Economic Accounts.

12. Estimate base year (2019) share of e-commerce to total output in industries related to wholesale trade.
$Base\ E\text{-}Com\ Emp_{i,j}^{Region} = Base\ E\text{-}Com\ Emp_i^{Region} \times Base\ SOC\ \%_{i,j}^{US}$

Where:

- $Base\ E\text{-}Com\ Emp_{i,j}^{Region}$ is the estimated regional 2019 B2B e-commerce employment by NAICS industry *i* and in Standard Occupational Classification (SOC) occupation *j*
- $Base\ SOC\ \%_{i,j}^{US}$ is the US' 2019 SOC occupation *j* share of total wholesale trade sector employment in NAICS industry *i* from US BLS data[1]

13. Estimate base year (2019) output (in 2012 chained dollars per hour) for e-commerce in industries related to wholesale trade.
$Base\ E\text{-}Com\ Output_i^{Region} = BaseProductivity^{US} \times Base\ E\text{-}Com\ Emp_i^{Region}$

Where:

- $Base\ E\text{-}Com\ Output^{Region}$ is the estimated regional 2019 wholesale trade or B2B e-commerce real gross output by NAICS industry *i*
- $Base\ Productivity^{US}$ is the US' 2019 real gross output per hour worked in wholesale trade or B2B sector from US BEA-BLS data[2]

14. Estimate future year (2045) e-commerce employment in industries related to wholesale trade.
$Future\ E\text{-}Com\ Emp^{Region} = Emp\ GF^{VA} \times Base\ E\text{-}Com\ Emp^{Region}$

Where:

- $Future\ E\text{-}Com\ Emp^{Region}$ is the estimated regional 2045 wholesale trade or B2B e-commerce employment by NAICS industry *i*
- $Emp\ GF^{VA}$ is a 2019 to 2045 employment growth factor in wholesale trade or B2B sector from Woods and Poole 2017 data and 2045 forecast for Virginia's employment[3]

15. Estimate future year (2045) e-commerce employment in industries related to wholesale trade by three-digit NAICS code and SOC code.
$Future\ E\text{-}Com\ Emp_{i,j}^{Region} = Future\ E\text{-}Com\ Emp_i^{Region} \times Future\ SOC\ \%_{i,j}^{US}$

Where:

- $Future\ E\text{-}Com\ Emp_{i,j}^{Region}$ is the estimated regional 2045 B2B e-commerce employment by NAICS industry *i* and in SOC occupation *j*
- $Future\ SOC\ \%_{i,j}^{US}$ is the US' 2029 SOC occupation *j* share of total wholesale trade sector employment in NAICS industry *i* from US BLS estimate

16. Estimate future year (2045) output (in 2012 chained dollars per hour) for e-commerce in industries related to wholesale trade.
$Future\ E\text{-}Com\ Output^{Region} = Future\ Productivity^{US} \times Future\ E\text{-}Com\ Emp^{Region}$

Where:

- $Future\ E\text{-}Com\ Output^{Region}$ is the estimated regional 2045 B2B e-commerce real gross output by NAICS industry *i*
- $Future\ Productivity^{US}$ is the US' estimated 2045 real gross output per hour worked (in 2012 chained dollars per hour) in B2B sector using the following trendline equation (log-normal) fitted based on historical (2010-2018) US real gross output per hour worked (in 2012 chained dollars per hour) in B2B sector from US BEA-BLS data: *Productivity in year* $X^{US} = 40.949 \times ln(X - 2000) + 48.782; R^2 = 0.88$

[1] US Bureau of Labor Statistics, Industry-occupation matrix data, by industry (last accessed on April 8, 2021)

[2] US Bureau of Economic Analysis, Integrated Industry-Level Production Account (KLEMS); GDP-by-industry tables; GDP & Personal Income tables (last accessed on April 8, 2021

[3] Provided by the Virginia Transportation Research Council (VTRC)

Estimate employment changes (full time equivalent) and output in dollars due to e-commerce for the Retail/Business-to-Consumer (B2C) market at the MSA level, for years 2019 and 2045.

17. Estimate the base year (2019) US share of total dollar value of B2C sales by state and 3-digit NAICS industry from calculation step # 6.

18. Estimate Virginia's base year (2019) retail e-commerce share of total sales by three-digit NAICS industry.
    $\text{Base E-Com Sales}^{VA} = \sum_i \text{Base E-Com Sales \%}_i^{US} \times \text{Base Total Sales}_i^{VA}$

    Where:
    - $\text{Base E-Com Sales}^{VA}$ is Virginia's estimated 2019 retail trade or B2C e-commerce share of total sales
    - $\text{Base E-Com Sales \%}_i^{US}$ is the US's estimated 2018 Q1-2020 Q3 average retail trade or B2C e-commerce share of total sales for NAICS industry *i*
    - $\text{Base Total Sales}_i^{VA}$ is Virginia's 2018 Q1-2020 Q3 B2C total taxable sales for NAICS industry *i* gathered from Virginia Department of Taxation's annual taxable B2C sales data published on the Weldon Cooper Center website[1]
    - *i* is the index for NAICS industries 441-448 and 451-454

19. Estimate the future year (2045) US share of total dollar value of retail trade or B2C sales by State and 3-Digit NAICS Industry using historical (2010-2018) US retail trade or B2C e-commerce shares of total sales gathered from US Census' US Annual Merchant Wholesaler data. The following trendline equation (polynomial) was fitted as follows:
    $\text{E-Com Sales \% in year } X^{US}$
    $= -1.10\times10^{-5} \times (X\text{-}2009)^3 + 5.5\times10^{-4} * (X\text{-}2009)^2 + 2.3\times10^{-3} \times (X\text{-}2009) + 4.2 \times 10^{-2}; R^2 = 0.99$

    Where:
    - $\text{E-Com Sales \% in year } X^{US}$ is the US' estimated wholesale trade or B2C e-commerce share of total sales in year *X* for a given NAICS industry

    The estimated 2045 national forecast retail trade or B2C e-commerce share of 33 percent based on the above equation was used as a control check on the total market size of retail trade or B2C e-commerce estimated for Virginia. Due to differences in industrial mix at national and state levels, the estimated shares may differ at these geographical levels.

    Through a study of research articles gathered on each 3-digit NAICS industry, 2045 medium scenario (most likely) assumptions were made on retail trade or B2C e-commerce shares. These are upward adjustments to the 2019 retail trade or B2C e-commerce shares. A range of +/-5 percent by industry was assumed to represent the 2045 low and high scenarios. The weights used for the 3-digit NAICS industries in 2019, that is $\text{Base Total Sales \%}_i^{VA}$, to estimate the retail trade or B2C sector level e-commerce share were also used in 2045.

Estimate changes in output (in 2012 chained dollars per hour) due to e-commerce for the Wholesale/Business-to-Business (B2B) market at the MSA level, for years 2019 and 2045.

20. Estimate base year (2019) share of e-commerce to total output in industries related to retail trade.
    $\text{Base E-Com Emp}_{i,j}^{Region} = \text{E-Com Emp}_i^{Regio} \times \text{Base SOC \%}_{i,j}^{US}$

    Where:
    - $\text{Base E-Com Emp}_{i,j}^{Region}$ is the estimated regional 2019 wholesale trade or B2B e-commerce employment by NAICS industry *i* and in SOC occupation *j*
    - $\text{Base SOC \%}i,j^{US}$ is the US' 2019 SOC occupation *j* share of total wholesale trade sector employment in NAICS industry *i* from US BLS data[2]

[1] Virginia Department of Taxation via Weldon Cooper Center for Public Service, Historical Virginia State Annual and Quarterly Taxable Sales by NAICS 3-digit Industry (last accessed on April 8, 2021)

[2] US Bureau of Labor Statistics, Industry-occupation matrix data, by industry (last accessed on April 8, 2021)

[3] US Bureau of Economic Analysis, Integrated Industry-Level Production Account (KLEMS); GDP-by-industry tables; GDP & Personal Income tables (last accessed on April 8, 2021)

21. Estimate base year (2019) output (in 2012 chained dollars per hour) for e-commerce in industries related to retail trade.
$\textit{Base E-Com Output}_i^{Region} = \textit{Base Productivity}^{US} \times \textit{Base E-Com Emp}_i^{Region}$

Where:

- $\textit{Base E-Com Output}_i^{Region}$ is the estimated regional 2019 retail trade or B2C e-commerce real gross output by NAICS industry i
- $\textit{Base Productivity}^{US}$ is the US' 2019 real gross output per hour worked in retail trade or B2C e-commerce sector from US BEA-BLS data[3]

22. Estimate future year (2045) e-commerce employment in industries related to retail trade.

$\textit{Future E-Com Emp}^{Region} = \textit{Emp GF}^{VA} \times \textit{Base E-Com Emp}^{Region}$

Where:

- $\textit{Future E-Com Emp}^{Region}$ is the estimated regional 2045 B2B e-commerce employment by NAICS industry i
- $\textit{Emp GF}^{VA}$ is the 2019 to 2045 employment growth factor in B2B sector from Woods and Poole 2017 data and 2045 forecast for Virginia's employment[1]

23. Estimate future year (2045) e-commerce employment in industries related to retail trade by 3-digit NAICS code and SOC code.
$\textit{Future E-Com Emp}_{i,j}^{Region} = \textit{Future E-Com Emp}^{Region} \times \textit{Future SOC \%}_{i,j}^{US}$

Where:

- $\textit{Future E-Com Emp}_{i,j}^{Region}$ is the estimated regional 2045 retail trade or B2C e-commerce employment by NAICS industry i and in SOC occupation j
- $\textit{Future SOC \%}_{i,j}^{US}$ is the US' 2029 SOC occupation j share of total retail trade sector employment in NAICS industry i from US BLS estimation

24. Estimate future year (2045) output (in 2012 chained dollars per hour) for e-commerce in industries related to retail trade.
$\textit{Future E-Com Output}^{Region} = \textit{Future Productivity}^{US} \times \textit{Future E-Com Emp}^{Region}$

Where:

- $\textit{Future E-Com Output}^{Region}$ is the estimated regional 2045 B2B e-commerce real gross output by NAICS industry i
- $\textit{Future Productivity}^{US}$ is the US' estimated 2045 real gross output per hour worked (in 2012 chained dollars per hour) in wholesale trade or B2B sector using the following trendline equation (log-normal) fitted based on historical (2010-2018) US real gross output per hour worked (in 2012 chained dollars per hour) in B2B sector from US BEA-BLS data: $\textit{Productivity in year } X^{US} = 1.9551 \times (X–2000) + 39.488$; $R^2=0.95$

[1] Provided by the Virginia Transportation Research Council (VTRC)

3.1.6. VTrans Macrotrend # 6: Greater Automation of Production and Services

Description: Contemporary automation consists of a collection of cyber-physical systems that are enabled by the internet of things (IoT), advancements in prototyping and manufacturing (e.g., robotics, precision instruments, 3D printing), and "big data" algorithms (machine learning and artificial intelligence) applied to data and information collected by sensors. These developments in automation create the opportunity for varying productivity gains and impacts by industry.

Drivers:

- Digitalization (the process of employing digital technologies that transform business operations) of goods production and distribution systems
- Increased use of machine learning and autonomous robots
- Expanded just-in-time and lean production
- Demand for faster "time to market" goods production[1]
- Growth in high level of automation fulfillment centers[2,3]

Significance: Production automation changes job estimates, goods movement, location of services and skills requirements. All of these have direct transportation and economic impacts.

Data Sources:

- Industry Occupation Matrix data: US Bureau of Labor Statistics[4]
- State and Metro Area Employment data: US Bureau of Labor Statistics[5]

[1] Dóra Horváth, Roland Zs. Szabó, Driving forces and barriers of Industry 4.0: Do multinational and small and medium-sized companies have equal opportunities?, Technological Forecasting and Social Change, 146 (2019), 119-132.

[2] CNBC, Walmart to ramp up automated fulfillment at stores as online grocery grows (cnbc.com), January 27, 2021.

[3] Azadeh, Kaveh, De Koster, Rene, and Roy, Debjit. Robotized and Automated Warehouse Systems: Review and Recent Developments, Transportation Science, Volume 53: Issue 4, July-August 2019. pp 917–945.

[4] US Bureau of Labor Statistics, Industry-occupation matrix data, by industry (last accessed on April 8, 2021)

[5] US Bureau of Labor Statstics, State and Metro Area Employment, Hours, & Earnings (last accessed on April 8, 2021)

- Virginia Employment forecasts: Woods & Poole[1]
- US Output (GDP) by Industry data: US Bureau of Economic Analysis[2]
- Freight Analysis Framework: US Bureau of Transportation Statistics and FHWA[3]
- US Census Commodity Flow Survey[4]

Calculations:

Quantify the level of Production Automation in Goods-Movement-Dependent Industries

1. Find base year (2019) employment (full time equivalent) for goods-movement-dependent industries at the two-digit NAICS code level by Virginia MSA/ and rural areas. Define MSAs by size:
   - Large MSAs: Richmond, Virginia Beach-Norfolk-Newport News and Northern Virginia
   - Medium MSAs: Charlottesville, Lynchburg, Roanoke
   - Rest of State: Small MSAs + Rural Areas

   Virginia's 2019 employment by region and 2-digit NAICS industry is collected from US BLS data[5].

2. Estimate future year (2045) employment (full time equivalent) for goods-movement-dependent industries at the two-digit NAICS code level by Virginia MSAs and rural areas.
   $Future\ Emp_i^{Region} = Emp\ GF_i^{VA} \times Base\ Emp_i^{Region}$

   Where:
   - $Future\ Emp_i^{Region}$ is the estimated regional 2045 employment for 2-digit NAICS industry *i*
   - $Emp\ GF_i^{VA}$ is the 2019 to 2045 employment growth factor for 2-digit NAICS industry *i* from Woods and Poole 2017 data and 2045 forecast for Virginia's employment[6]
   - $Base\ Emp_i^{Region}$ is the regional 2019 employment for 2-digit NAICS industry *i* from US BLS data
   - *i* is the index for 2-digit NAICS goods movement dependent industries

3. Estimate base year (2019) output in dollars for goods-movement-dependent industries at the two-digit NAICS code level by Virginia MSAs and rural areas. Use US 2019 real gross output per hour worked (in 2012 chained dollars per hour) or productivity for goods movement dependent industries[7] from US BEA-BLS data.[8]
   - Estimate the future year (2045) productivity for the US for goods-movement-related industries. As output forecasts were not available from Woods and Poole, use a set of future productivity trendline equations based on historical (2010-2018) productivity data on goods-movement-dependent industries, as shown below.
   - For mining, logging, and construction: a growth factor of 1.0 was used for this industry as the historical data did not show a consistent trend
   - For manufacturing: $Productivity\ in\ year\ X^{US} = 29.305 \times \ln(X-2000) + 164.93;\ R^2=0.96$
   - For wholesale trade: $Productivity\ in\ year\ X^{US} = 40.949 \times \ln(X-2000) + 48.782;\ R^2=0.88$
   - For retail trade: $Productivity\ in\ year\ X^{US} = 1.9551 \times (X-2000) + 39.488;\ R^2=0.95$
   - For transportation, warehousing, and utilities: a growth factor of 1.0 was used for this industry as the historical data did not show a consistent trend

   This is used to estimate $Future\ Productivity_i^{US}$ (defined as US 2045 real gross output per hour worked in 2012 chained dollars per hour for goods-movement-dependent industries in the next step.

[1] Provided by the Virginia Transportation Research Council (VTRC)

[2] US Bureau of Economic Analysis, Integrated Industry-Level Production Account (KLEMS); GDP-by-industry tables; GDP & Personal Income tables (last accessed on April 8, 2021)

[3] US Bureau of Transportation Statistics and Federal Highways Admnistration. Freight Analysis Framework. Last accessed July 15, 2021.

[4] US Census, Commodity Flow Survey, last accessed July 15. 2021.

[5] US Bureau of Labor Statistics, State and Metro Area Employment, Hours, & Earnings data (last accessed on April 8, 2021)

[6] Provided by the Virginia Transportation Research Council (VTRC)

[7] Note: includes manufacturing, wholesale trade, retail trade, transportation, warehousing, utility, mining and construction sectors

[8] US Bureau of Economic Analysis, Integrated Industry-Level Production Account (KLEMS); GDP-by-industry tables; GDP & Personal Income tables (last accessed on April 8, 2021)

4. Estimate future year (2045) output in dollars for goods-movement-dependent industries at the two-digit NAICS code level by Virginia MSAs and rural areas
   $Future\ Output_i^{Region} = Future\ Productivity_i^{US} \times Future\ Emp_i^{Region}$

   Where:
   - $Future\ Output_i^{Region}$ is the estimated regional 2045 baseline real gross output for 2-digit NAICS industry *i*
   - $Future\ Productivity_i^{US}$ is the estimated US 2045 real gross output for hour worked for NAICS industry i, from calculation step # 3.
   - $Future\ Emp_i^{Region}$ is the estimated regional 2045 employment for 2-digit NAICS industry i, from calculation step # 2.

Estimate 3D Printing as share of total manufacturing output (in dollars) for the state and 3-digit NAICS industry level for years 2019 and 2045

5. Estimate base year (2019) 3D printing market share (in dollars).
   $Base\ 3DP\ \%^{VA} = Base\ 3DP\ Market\ Value^{US} / Base\ Mfg\ Value\ Added^{US}$

   Where:
   - $Base\ 3DP\ \%^{VA}$ is Virginia's estimated 2019 3D printing share of total manufacturing output
   - $3DP\ Market\ Value^{US}$ is the US' 2019 3D printing market value in the U.S. Use Deloitte[1] estimations for the 2019 3D printing market value.
   - $Base\ Mfg\ Value\ Added^{US}$ is the US' 2019 real value added by manufacturing sector of U.S. economy in 2012 chained dollars from US BEA data[2]

Estimate 2019-2045 manufacturing sector growth factor for Virginia.

$Mfg\ GF = (Base\ Mfg\ Output^{VA} / Future\ Mfg\ Output^{VA})$

Where:
- $Base\ Mfg\ Output^{VA}$ *and* $Future\ Mfg\ Output^{VA}$ come from the sum of the base year output by MSA and rural areas in calculation Step 3 and the future output by MSA and rural areas in calculation step 4.

6. Estimate future year (2045) 3D printing market share (in dollars).
   $Future\ 3DP\ \%^{VA} = Future\ 3DP\ Market\ Value^{US} / (Base\ Mfg\ Value\ Added^{US} \times Mfg\ GF)$

   Where:
   - $Future\ 3DP\ \%^{VA}$ is Virginia's estimated 2045 3D printing share of total manufacturing output
   - $Future\ 3DP\ Market\ Value^{US}$ is the US' 2045 3D printing market value in the U.S. assumption
   - *Mfg GF* is Virginia's estimated 2019-2045 manufacturing sector growth factor

   The following sources and methods formed the basis for future 3D printing scenario assumptions:

   - **Low scenario:** Deloitte[3] estimated an annualized growth rate of 3D printing market value of 12.6 percent over the period of 2017-2020. This high annualized growth rate was expected to slow down with the turn of each decade. The annualized growth rate of 12.6 percent was maintained for the period 2021-2030, and then gradually reduced it to 6.3 percent (50 percent of the assumed growth rate in 2020-2030) for the period 2031-2040. It was further reduced to 3.1 percent (50 percent of the assumed growth rate in 2030-2040) for the period 2041-2045. The resulting 3D printing market value in the U.S. is estimated to be $21.7 billion in 2045, that is, about eight times the base (2019) market value.
   - **Medium scenario:** As per a Congressional Research Service (CRS) report on 3D printing[4], most experts expect 3D printing to form 5-10 percent of global manufacturing revenues (currently assumed as 7.5 percent). This is possible to achieve if the U.S. 3D printing market growth exceeds the global average in the short-term. The medium scenario or

[1] Deloitte Insights, "3D printing growth accelerates again" December 11, 2018. (last accessed on April 8, 2021)

[2] US Bureau of Economic Analysis, GDP-by-industry tables; (last accessed on April 8, 2021)

[3] Deloitte Insights, "3D printing growth accelerates again" December 11, 2018. (last accessed on April 8, 2021)

[4] Congressional Research Service Report, 3D Printing: Overview, Impacts, and the Federal Role, Prepared for Members and Committees of Congress, August 2, 2019.

the most likely value for the 3D printing market in the U.S. was thus determined as $167.8 billion.

- **High scenario:** As per an AT Kearney analysis[1], the U.S. 3D printing market is estimated to reach a value of $300-$500 billion dollars in the next 10 years, which was considered very aggressive. For the purpose of this trend analysis, the market was capped at $300 billion and used as the future year (2045) high scenario.

Estimate 3D printing-related employment (full-time equivalent) and output in dollars at the 3-digit NAICS industry and SOC (for employment only) level, for years 2019 and 2045

7. Estimate base year (2019) 3D printing-related employment (full-time equivalent) at the 3-digit NAICS industry level.
   $Base\ 3DP\ Emp_i^{Region} = Base\ Mfg\ Emp_i^{VA} \times Base\ 3DP\ \%^{US} \times 3DP\ Industry\ \%_i^{US} \times Base\ Mfg\ Emp\%^{Region}$

   Where:
   - $Base\ 3DP\ Emp_i^{Region}$ is the estimated regional 2019 3D printing employment by 3-digit NAICS industry *i*
   - $Base\ Mfg\ Emp_i^{VA}$ is Virginia's 2019 Quarter 4 Month 3 manufacturing sector employment by 3-digit NAICS industry *i* [2]
   - $Base\ 3DP\ \%^{US}$ is derived from calculation step 5 (same as Virginia estimate)
   - $3DP\ Industry\ \%_i^{US}$ is the assumed share for the 3D printing industry for 3-digit NAICS industry *i*
   - $Base\ Mfg\ Emp\%^{Region}$ is the regional 2019 employment share of Virginia's total employment in manufacturing sector[3]
   - *i* is the index for 3-digit NAICS industries suited to 3D printing (315 - Apparel Manufacturing, 326 - Plastics and Rubber Products Manufacturing, 327 - Nonmetallic Mineral Product Manufacturing, 332 - Fabricated Metal Product Manufacturing, 333 - Machinery Manufacturing, 334 - Computer and Electronic Product Manufacturing, 335 - Electrical Equipment, Appliance, and Component Manufacturing, 336 - Transportation Equipment Manufacturing and 339 - Miscellaneous Manufacturing)

8. Estimate base year (2019) 3D printing-related employment (full-time equivalent) at the 3-digit SOC industry level.
   $Base\ 3DP\ Emp_{i,j}^{Region} = Base\ 3DP\ Emp_i^{Region} \times Base\ SOC\ \%_{i,j}^{US}$

   Where:
   - $Base\ 3DP\ Emp_{i,j}^{Region}$ is the estimated regional 2019 3D printing employment by NAICS industry *i* and in SOC occupation *j*
   - $Base\ SOC\ \%_{i,j}^{US}$ is the US' 2019 SOC occupation *j* share of total manufacturing sector employment in NAICS industry *i* from US BLS data[4]

9. Estimate base year (2019) 3D printing-related output by Virginia MSA's and rural areas.
   $Base\ 3DP\ Output_i^{Region} = Base\ Productivity^{US} \times Base\ 3DP\ Emp_i^{Region}$

   Where:
   - $Base3DP\ Output^{Region}$ is the estimated regional 2019 3D printing real gross output by NAICS industry *i*
   - $Base\ Productivity^{US}$ is the US' 2019 real gross output per hour worked (in 2012 chained dollars per hour) in manufacturing sector from US BEA-BLS data[5]

10. Estimate future year (2045) 3D printing-related Employment (full time equivalent) at the 3-digit NAICS industry level.
    $Future\ 3DP\ Emp^{Region} = Emp\ GF^{VA} \times Base3DP\ Emp^{Region}$

    Where:
    - $Future\ 3DP\ Emp^{Region}$ is the estimated regional 2045 3D printing employment by NAICS industry *i*
    - $Emp\ GF^{VA}$ is the 2019 to 2045 employment growth factor in manufacturing sector from Woods and Poole 2017 data and 2045 forecast for Virginia's employment[6]

[1] HP and AT Kearney, 3D Printing: Ensuring Manufacturing Leadership in the 21st Century, 2017.

[2] US Bureau of Labor Stastistics, Occupational Employment and Wage Statistics (last accessed on April 8, 2021)

[3] US Bureau of Labor Stastistics, Occupational Employment and Wage Statistics (last accessed on April 8, 2021)

[4] US Bureau of Labor Statistics, Industry-occupation matrix data, by industry (last accessed on April 8, 2021)

[5] US Bureau of Economic Analysis, Integrated Industry-Level Production Account (KLEMS); GDP-by-industry tables; GDP & Personal Income tables (last accessed on April 8, 2021)

[6] Provided by the Virginia Transportation Research Council (VTRC)

Estimate base year (2019) 3D printing-related employment (full-time equivalent) at the 3-digit SOC industry level.

$Future\ 3DP\ Emp_{i,j}^{Region} = Future\ 3DP\ Emp_{i}^{Region} \times Future\ SOC\ \%_{i,j}^{US}$

Where:

- $Future\ 3DP\ Emp_{i,j}^{Region}$ is the estimated regional 2045 3D printing employment by NAICS industry *i* and in SOC occupation *j*
- $Future\ SOC\ \%_{i,j}^{US}$ is the US' 2029 SOC occupation *j* share of total manufacturing sector employment in NAICS industry *i* from US BLS estimate

11. Estimate future year (2045) real gross output per hour worked (in 2012 chained dollars per hour) in manufacturing sector using the following trendline equation (log-normal) fitted based on historical (2010-2018) US real gross output per hour worked (in 2012 chained dollars per hour) in manufacturing sector from US BEA-BLS data:
$Productivity\ in\ year\ X^{US} = 29.305 \times ln(X\text{–}2000) + 164.93;\ R^2 = 0.96$

12. Estimate future year (2045) 3D printing-related output by Virginia MSA's and rural areas.
Future 3DP Output Region = Future ProductivityUS × Future 3DP EmpRegion

Where:

- $Future\ 3DP\ Output^{Region}$ is the estimated regional 2045 3D printing real gross output by NAICS industry *i*
- $Future\ Productivity^{US}$ is the estimated future year (2045) real gross output per hour worked (calculation step # 11).
- *Future 3DP EmpRegion* is the estimated regional 2045 3D printing employment by NAICS industry *i* calulated in step 10

Estimate the ratio between value-per-ton for 3D printing commodities and value-per-ton for average goods-movement-dependent industry commodities for Virginia

13. Use US BTS and FHWA's Freight Analysis Framework Version 5 (FAF5) database for value-per-ton for 3D printing-friendly goods[1] traveling to/from/within Virginia. This was estimated as $3,617 per ton, which was assumed to be a typical value-per-ton for 3D printed commodities. Using the same data, estimate overall value-per-ton of goods traveling to/from/within Virginia as $1,096 per ton. The value-per-ton ratio between 3D printed commodities and all goods-movement-dependent industry commodities was therefore estimated as 3.3.

Estimate gross truck tons change over base year (due to re-allocation from long-haul domestic and international cargo markets to short-haul domestic and national cargo markets) for Virginia MSAs and rural areas and truck class

14. Gross truck tons change due to 3D printing over base year conditions was assumed to be zero. However, shifts in sourcing and distribution of 3D printed commodities are assumed between the truck types. The commodity shifts were guided by the market shares in US BTS and FHWA's Freight Analysis Framework Version 5 (FAF5) data for Virginia and allocation of truck types to the markets.

Estimate the Long-Range Drone Delivery Share of total dollar value of domestic air cargo industry (within 500 miles and more than 55 pounds of drone weight) for Virginia

[1] Note: Includes the Standard Classification of Transported Goods (SCTG) commodities of Articles-base metal, Electronics, Machinery, Misc. mfg. prods., Motorized vehicles, Nonmetal min. prods., Plastics/rubber, Precision instruments, Textiles/leather, and Transport equip.

15. Estimate base year (2019) Long-Range Drone Delivery Share of total dollar value of domestic air cargo industry.
Base LRDrone $\%^{VA}$ *= Base Civil UAV Market Value*^{Global}*/Base Civil Air Industry Value*^{Global}

Where:

- *Base Civil UAV Market Value*^{Global} is the estimated global 2019 civil long-range drone or UAV market value from industry forecasts,[1] which is $5 billion US dollars
- *Base Civil Air Industry Value*^{Global} is the estimated global 2019 civil aviation market value from industry forecasts,[2] which is $875 billion US dollars.

16. Estimate future year (2045) Long-Range Drone Delivery Share of total dollar value of domestic air cargo industry. The following sources and methods formed the basis for future long-range drone scenario assumptions.
    - **Low Scenario:** It is assumed that long-range drones use will not grow faster than US domestic air cargo market which is 1.9 percent per year. The long-range drone market share of the domestic air cargo is assumed to remain at the base value of 0.6 percent estimated using the year 2019 calculation.
    - **Medium and High Scenarios:** Long-range drones will grow at a rate of 10.5 percent per year, which is much faster than the US domestic air cargo market. The long-range drone market share of the domestic air cargo will reach 4.6 percent.

Estimate the Ratio between value-per-ton for long-range drone delivery commodities and value-per-ton for average goods movement-dependent industry commodities for Virginia

17. Using the 2017 Commodity Flow Survey, value-per-ton for Virginia specific shipments by air to distances between 50 miles and 500 miles and less than 500 pounds by weight was estimated.
Value-per-ton Ratio = Long-range drone value-per-ton / Overall goods traveling to/from/within Virginia value-per-ton

$174,687 per ton was assumed to be a typical value-per-ton for long-range drone commodities. Using the US BTS and FHWA FAF5 data, the overall value-per-ton of goods traveling to/from/within Virginia was estimated as $1,096 per ton. The value-per-ton ratio between long-range drone commodities and all goods-movement-dependent industry commodities was estimated as 159.4.

Estimate the Short-Range Drone Delivery Share of total dollar value of B2C (retail) e-commerce sales for Virginia

18. Estimate base year (2019) short-range drone market share of B2C e-commerce. Define short-range drone delivery as those within 20 miles and less than 55 pounds of drone weight. Short-range drone delivery market share of B2C e-commerce in Virginia currently is assumed be negligible.

19. Estimate base year (2019) short-range drone market share of B2C e-commerce. Short-range drone delivery calculations assumed the B2C e-commerce share of total retail trade or B2C sales to be at the baseline level of 7.6 percent. The market potential for short-range drones was assumed as the percentage of e-commerce deliveries requiring same-day delivery, which is 25 percent as per an industry report.[3] The following future short-range drone scenario assumptions were additionally made:
    - **Low Scenario:** Slow market penetration due to the inability to operate short-range drones in some conditions: e.g., GPS signal is blocked by buildings or other fixed objects, perceived safety/regulation issues, insurance issues, and overcrowding of air space below 400 feet. Under this 20 percent of the market potential was assumed by 2045, that is 5 percent of retail trade e-commerce deliveries are assumed to use short-range drones.

[1] Teal Group, World Civil UAS Market Profile and Forecast: 2020/2021: (last accessed on April 8, 2021)
[2] International Air Transport Association, Economic Performance of the Airline Industry (last accessed on April 8, 2021)
[3] McKinsey & Company, "Parcel delivery; The future of last mile", September 2016. (last accessed on April 8, 2021)

- **Medium Scenario:** Short-range drones are assumed to serve 50 percent of the market potential by 2045, that is 12.5 percent of retail trade e-commerce deliveries.
- **High Scenario:** Short-range drones are assumed to serve 100% of the market potential for UAV delivery by 2045, that is 25 percent of retail trade e-commerce deliveries. This is driven by the lowering of drone cost per package cost, increase in weight capacity, and increase in the density of same-day delivery traffic.

Estimate the ratio between value-per-ton for short-range drone delivery commodities and value-per-ton for average goods movement-dependent industry commodities

20. Using the 2017 CFS,[1] value-per-ton for Virginia specific shipments by air and truck to distances less than 50 miles and less than 50 pounds by weight was estimated as $25,731 per ton, which was assumed to be a typical value-per-ton for short-range drone commodities. Using the US BTS and FHWA FAF5 data, the overall value-per-ton of goods traveling to/from/within Virginia was estimated as $1,096 per ton. The value-per-ton ratio between short-range drone commodities and all goods movement dependent industry commodities was estimated as 23.5.

[1] U.S. Department of Transportation. 2017 Commodity Flow Survey.

3.1.7. VTrans Macrotrend # 7: Growth of Professional Services Industry

Description: This trend refers to changes in the number and proportion of jobs in the professional and technical services industry.

Drivers: The drivers of this macrotrend include:

- Digitalization of the economy
- Changing economic forces moving the US to a service-based economy

Significance: Transportation infrastructure and services demand is influenced by commuting patterns, which vary by job type and location. Professional and technical services jobs tend to cluster in urban areas, for example.

Data source(s):

- Historic and Forecast Employment Estimates for Virginia: Weldon Cooper Center for Public Service[1]
- Historic and Forecast Employment Estimates for Virginia: Woods & Poole[2]
- Virginia Employment by 3-Digit NAICS Industry: US Bureau of Labor Statistics[3]
- Ten-year Occupation Projections: US Bureau of Labor Statistics[4]
- STEM Occupations Share of All Occupations by 2-Digit NAICS Industry: US Bureau of Labor Statistics[5]

[1] Weldon Cooper Center for Public Service at University of Virginia

[2] Woods & Poole forecasts provided by the Virginia Transportation Research Council (VTRC)

[3] US Bureau of Labor Statistics, QCEW Data Views, 2019 US BLS Quarter 4 Month 3 State Virginia Employment by 3-Digit NAICS Industry, last accessed July 22, 2021.

[4] US Bureau of Labor Statistics, Occupational Projections Data, last accessed July 22, 2021.

[5] US Bureau of Labor Statistics, Standard Occupational Classification (SOC) System datasets, Stem Occupation list, last accessed July 22, 2021.

Calculations

1. Develop a working definition of STEM related jobs for the purposes of this analysis. Instead of using industry designation, use occupational categorization to develop a listing of occupations assigned by the Bureau of Labor Statistics as "STEM" occupations.

   Estimate the current year (2019) percentage of STEM occupation employment by Virginia County.

2. Determine the current percentage of STEM occupation employment per NAICS 2-digit industry nationally, and apply that national percentage to jobs by NAICS industry for job estimates in Virginia localities.
   $EmploymentSTEM_{ilocality} = \Sigma\ (EmploymentSTEM_i \times Employment_i)$

   Where:

   $EmploymentSTEM_{ilocality}$ is the estimated STEM occupation jobs per Virginia locality
   $EmploymentSTEM_i$ is the national percentage of STEM occupation per 2-digit NAICS industry
   $Employment_{ilocality}$ is the estimated jobs by NAICS 2-digit industry per Virginia locality

3. Aggregate to the PDC, VDOT Construction District, and Statewide level.

   Estimate the future year (2045) percentage of STEM occupation employment by Virginia County.

4. Estimate the 2045 Employment by 2-digit NAICS industry by Virginia locality.

5. Use the 10-year employment growth rates for STEM occupation employment from BLS to determine 2019-2029 STEM growth rates as a percentage of jobs by NAICS 2-digit industry.

6. Apply this 10-year BLS growth rate again two times to estimate a 2049 STEM growth rates as a percentage of jobs by NAICS 2-digit industry.

7. Use the 2019-2049 growth rate to develop a proxy for a 2045 (2049) STEM percentage of jobs by NAICS 2-digit industry.

8. Using the 2045 employment estimated in Step 4 and the STEM percentage of jobs in step 7, estimate the number of STEM jobs in 2045 by Virginia locality.

9. Aggregate to the PDC, VDOT Construction District, and statewide levels.

3.1.8. VTrans Macrotrend # 8: Increase in Workplace Flexibility

Description: Remote working or telecommuting is the ability to work from home or from a location other than the employer office or jobsite through the use of the internet, email, telephone, and other communications technologies. The macrotrend estimates the number of workers that can potentially work from home based on industry in Virginia.

Significance: This trend will lead to greater flexibility in terms of where people choose to live and their commute and travel patterns. As job availability by industry and location change, it may affect the geographic distribution of where workers live and change travel demand on the Commonwealth's transportation system.

Drivers:

- Advancement of workplace communication technology[1] and collaboration tools
- Availability, reliability, and speed of broadband services[2]
- Growth in knowledge worker jobs[3]

Data Sources:

- Share of jobs that are work-from-home capable: Dey et al.[4]
- Share of jobs that are work-from-home capable; pre-COVID work-from-home take-up rates: Dingel and Neiman[5]
- Virginia Industry Projections: Virginia Employment Commission[6]
- Work-from-home Survey Report: Global Workplace Analytics[7]

[1] The State of Video Conferencing in 2020, Massive-uptick-in-collaboration-software-usage-in-2020

[2] Pew Research, Internet/Broadband Fact Sheet

[3] Wall Street Journal, The Rise of Knowledge Workers Is Accelerating Despite the Threat of Automation

[4] Dey, Matthew, Harley Frazis, Mark A. Loewenstein, and Hugette Sun (2020). "Ability to Work from Home: Evidence from Two Surveys and Implications for the Labor Market in the COVID-19 Pandemic : Monthly Labor Review: U.S. Bureau of Labor Statistics."

[5] Dingel, Jonathan I., and Brent Neiman. "How Many Jobs Can Be Done at Home?" Journal of Public Economics 189 (September 2020): 104235. Data tables found here.

[6] Virginia Employment Commission. "Industry Projections." Accessed February 1, 2021.

[7] Global Workplace Analytics (2020). "Global Work-from-Home Experience Survey Report." May 2020.

- Remote Work Survey: PricewaterhouseCoopers[1]
- Employment Data: US Census Bureau[2]

Calculations:

1. Estimate Virginia's share of workplace-flexible (WF) jobs at the two-digit NAICS industry level using occupational behavior survey results and methodology based on Dingel and Neiman[3] and Dey et al.[4] Results are shown below in Table 8 as column (a) and based on the average rate between the two studies.
% WF jobs = # of jobs that are remote work capable by NAICS industry/Total # of jobs in NAICS industry

2. Utilize the results from Dey et al. to estimate a pre-COVID "take-up rate" of flexible workplace arrangements by two-digit NAICS industry. Take-up rate refers to the percent of workplace-flexible (WF) job respondents that actually worked from home on the survey day. Results are shown below in Table 9.
Pre COVID WF Takeup Rate is the number of workers that worked remotely prior to the COVID pandemic/ Total # of workers surveyed

3. Calculate the difference in workplace-flexible (WF) jobs between the pre-COVID take-up rate and full (100%) capability. The delta was again averaged between the two research sources (Dingel and Neiman and Dey et al). Results are shown below in Table 8 as column (c).
%WF Jobs, Delta = %WF jobs by industry x (1 – Pre-COVID WF takeup rate by industry)

   Where:
   - *%WF Jobs, Delta* is the number of additional workers who could potentially switch to remote work. Recall that the Pre-COVID WF takeup rate by industry indicates the percent of workers that could work from home that did already prior to COVID-19.
   - *%WF jobs by industry*[5] is from calculation step # 1.
   - *Pre-COVID WF takeup rate by industry*[6] is from calculation step # 2.

Table 9: Remote Work Capability and Utilization by Two-digit NAICS Industry Code

Two-Digit NAICS Code[7]	Industry Title	WF Jobs[8]	Pre-COVID WF take-up rate[9]	Additional Potential WF jobs[10]
11	Agriculture, Forestry, Fishing and Hunting	7.97%	20.40%	6.34%
21	Mining, Quarrying, and Oil and Gas Extraction	40.67%	26.30%	29.98%
22	Utilities	31.20%	22.20%	24.27%
23	Construction	17.93%	13.00%	15.60%

[1] PricewaterhouseCoopers (2021). "Business Needs a Tighter Strategy for Remote Work." PwC. Accessed January 19, 2021.
[2] U.S. Census Bureau. Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics (LODES).
[3] Dingel, Jonathan I., and Brent Neiman. "How Many Jobs Can Be Done at Home?" *Journal of Public Economics* 189 (September 2020): 104235.
[4] Dey, Matthew, Harley Frazis, Mark A. Loewenstein, and Hugette Sun. "Ability to Work from Home: Evidence from Two Surveys and Implications for the Labor Market in the COVID-19 Pandemic: Monthly Labor Review: U.S. Bureau of Labor Statistics." Accessed January 27, 2021.
[5] Dingel, Jonathan I., and Brent Neiman. "How Many Jobs Can Be Done at Home?" *Journal of Public Economics* 189 (September 2020): 104235
[6] Dey, Matthew, Harley Frazis, Mark A. Loewenstein, and Hugette Sun. "Ability to Work from Home: Evidence from Two Surveys and Implications for the Labor Market in the COVID-19 Pandemic: Monthly Labor Review: U.S. Bureau of Labor Statistics." Accessed January 27, 2021.
[7] Not all NAICS were available: if not available, defaulted to NLSY79 datapoint: "Industry missing - 30.4%"
[8] Averaged across calculations on two research sources: Dingel and Neiman and Dey et al.
[9] Dey, Matthew, Harley Frazis, Mark A. Loewenstein, and Hugette Sun. "Ability to Work from Home: Evidence from Two Surveys and Implications for the Labor Market in the COVID-19 Pandemic: Monthly Labor Review: U.S. Bureau of Labor Statistics." Accessed January 27, 2021.
[10] Averaged across calculations on two research sources: Dingel and Neiman and Dey et al.

Two-Digit NAICS Code	Industry Title	WF Jobs	Pre-COVID WF take-up rate	Additional Potential WF jobs
31-33	Manufacturing	29.44%	31.60%	20.14%
42	Wholesale Trade	39.33%	19.30%	31.74%
44-45	Retail Trade	20.62%	19.30%	16.64%
48-49	Transportation and Warehousing	22.01%	22.20%	17.12%
51	Information	71.45%	36.90%	45.09%
52	Finance and Insurance	77.05%	29.60%	54.24%
53	Real Estate and Rental and Leasing	41.81%	30.40%	29.10%
54	Professional, Scientific, and Technical Services	75.09%	40.80%	44.45%
55	Management of Companies and Enterprises	82.89%	29.70%	58.27%
56	Administrative and Support and Waste Management and Remediation Services	31.06%	30.40%	21.62%
61	Educational Services	65.77%	15.80%	55.38%
62	Health Care and Social Assistance	37.08%	15.80%	31.22%
71	Arts, Entertainment, and Recreation	29.75%	30.40%	20.71%
72	Accommodation and Food Services	8.27%	12.70%	7.22%
81	Other Services (except Public Administration)	31.12%	14.00%	26.76%
99	Federal, State, and Local Government, excluding state and local schools and hospitals and the U.S. Postal Service (OES Designation)	53.34%	16.50%	44.54%

4. Estimate base year (2018) jobs that are workplace-flexible by Virginia locality (counties and independent cities). Use the 2018 (LEHD/LODES)[1] job location data and apply the WF jobs percentage to each county in Virginia for the number of jobs in each two-digit industry.
   # of WF jobs$_{2018}$ = *%WF Jobs, Delta x LEHD/LODES jobs data by industry*

   Where:
   - *# of WF jobs*$_{2018}$ is the number of additional workplace flexible jobs in 2018.
   - *%WF Jobs, Delta* is the additional jobs that could potentially switch to remote work from calculation step # 3.
   - *LEHD/LODES jobs data by industry* is *the number of jobs by NAICS sector.*

[1] US Census Bureau. Longitudinal Employer-Household Dynamics

5. Develop future year (2045) estimations for WF jobs by county based on industry-specific job growth projections from the Virginia Employment Commission (VEC).[1]

   $\# \text{ of WF jobs}_{2045} = \# \text{ of WF jobs}_{2018} \times \text{VEC projected growth rate by industry}$

   Where:

   - *# of WF jobs*$_{2045}$ is the number of additional workplace flexible jobs in 2045.
   - *# of WF jobs*$_{2018}$ is the number of additional workplace flexible jobs in 2018 from calculation step # 4.
   - *VEC projected growth rate by industry* is the percent growth rate estimated from the Virginia Employment Commission by NAICS industry extrapolated to project job growth between 2018 and 2045.

[1] Virginia Employment Commission. "Industry Projections." Accessed February 1, 2021.

3.1.9. VTrans Macrotrend # 9: Growth of the 65+ Cohort

Description: This trend refers to changes in the relative proportion of Virginia's population over age 65.

Drivers: The drivers of this macrotrend include:

- Migration patterns
- Location preferences of the population over the age of 65
- Overall population growth
- Natural increase (ratio of births to deaths)
- Historical births (Baby Boomer cohort)
- Advancements in medicine

Significance: Transportation infrastructure and services demand is influenced by household characteristics such as age of household occupants. Transportation systems may need to accommodate the changing needs of an aging population differently.

Data Sources:

- Historic and Forecast Population Estimates for Virginia: Weldon Cooper Center for Public Service[1]
- Historic and Forecast Population Estimates for Virginia: Woods & Poole[2]
- Population Estimates by Age and Sex (Virginia Localities): US Census Bureau[3]

Please refer to Appendix 2, Table 8, Number and Share of Population over Age 65.

[1] Weldon Cooper Center for Public Service, Annual Population Estimates and Population Projections

[2] Woods & Poole Economics, Inc. *Virginia, Maryland, and The District of Columbia, 2018 State Profile, State and County Projections to 2050.* 2018

[3] U.S. Census Bureau. *2017 Population Estimates: Age and Sex (Virginia Localities)*, Weldon Cooper Center for Public Service. 2018

3.1.10. VTrans Macrotrend # 10: Population and Employment Shift

Description: This trend refers to changes in the geographic distribution of population and the geographic and industry-level distribution of employment in Virginia.

Drivers:

- Macroeconomic factors such as industry agglomeration
- Location preferences of business
- Location preferences of households

Significance: Location preferences resulting from population and employment shifts cause change in demand for transportation infrastructure and services.

Data Sources:

- Historic and Forecast Population Estimates for Virginia and subgeographies: Weldon Cooper Center for Public Service[1]
- Historic and Forecast Population Estimates and Historic and Forecast Employment Estimates for Virginia: Woods & Poole[2]
- Forecast Employment Growth in Virginia: IHS Markit[3]
- Historical Employment for Virginia: US Bureau of Labor Statistics[4]

[1] Weldon Cooper Center for Public Service, Annual Population Estimates and Population Projections

[2] Woods & Poole Economics, Inc. *Virginia, Maryland, and The District of Columbia, 2018 State Profile, State and County Projections to 2050.* 2018

[3] Jeafarqomi, K. *Email to John S. Miller.* December 13, 2018

[4] Bureau of Labor Statistics. *Quarterly Census of Employment and Wages,* Washington, D.C., undated. Accessed January 25, 2019

Calculations: For baseline population and employment projections, refer to Appendix 2.

For estimated changes in industry employment by location:

1. Gather historical employment trends from the Bureau of Labor Statistics. Refer to Appendix 2, Table 9.
2. Gather 2018 employment by NAICS 2-digit industry classification by Virginia locality.[1]
3. Gather ten-year expected growth rates by NAICS 2-digit industry classification for Virginia Local Workforce Development Areas.[2]

Step 1: Macrotrend # 10: Population and Employment Shift Output

Please refer to Appendix 2, for number and relative share of population and employment in Virginia.

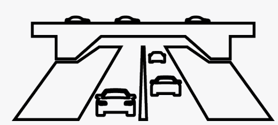
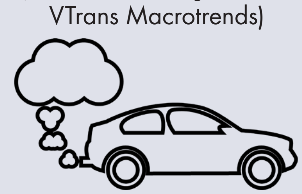
[1] US Census, Longitudinal Employer-Household Dynamics, Origin-Destination Employment Statistics

[2] Virginia Employment Commision, Long-term Projection by Industry, Virginia 2018-2028 Projections

3.2. Step 2: Identify Surrogates for CTB Goals

Step 2 identifies five surrogates for CTB's five Goals and associated Objectives[1] (Table 10). These proxies were established after an evaluation of availability of research, tools, and methods, and are considered fundamental blocks upon which a more comprehensive set of surrogates can be developed in the future. Surrogate indicators stand in for one or more aspects of the relevant goal and allow for progress toward the goal to be quantitatively tracked.

Table 10: Surrogates for CTB Goals

Goals	Objectives	Surrogates for CTB Goals and Objectives
Goal A Economic Competitiveness and Prosperity	A.1. Reduce the amount of travel that takes place in severe congestion	Vehicles Miles Traveled (VMT) Index 
	A.2. Reduce the number and severity of freight bottlenecks	
	A.3. Improve reliability on key corridors for all modes	
Goal B Accessible and Connected Places	B.1. Reduce average peak-period travel times in metropolitan areas	Shared Mobility Index (Switchable Urban Auto SOV VMT to Micromobility and TNC/Ridesourcing) 
	B.2. Reduce average daily trip lengths in metropolitan areas	
	B.3. Increase the accessibility to jobs via transit, walking, and driving in metropolitan areas	
Goal C Safety for All Users	C.1. Reduce the number and rate of motorized fatalities and serious injuries	Safety Index (Safety Index - Estimated Change in Number of Crashes with Fatalities + Serious Injuries Due to VTrans Macrotrends) 
	C.2. Reduce the number of non-motorized fatalities and serious injuries	
Goal D Proactive System Management	D.1. Improve the condition of all bridges based on deck area	Roadways At-Risk from Flooding 
	D.2. Increase the lane miles of pavement in good or fair condition	
	D.3. Increase percent of transit vehicles and facilities in good or fair condition	
Goal E Healthy Communities and Sustainable Transportation Communities	E.1. Reduce per-capita vehicle miles traveled	Tailpipe Emissions Index (Estimated Change Due to VTrans Macrotrends) 
	E.2. Reduce transportation related NOX, VOC, PM, and CO emissions	
	E.3. Increase the number of trips traveled by active transportation (bicycling and walking)	

[1] Commonwealth Transportation Board, Actions to Approve the 2019 VTrans Vision, Goals, Objectives, Guiding Principles and the 2019 Mid-term Needs Identification Methodology and Accept the 2019 Mid-term Needs, January 15, 2020

3.3. Step 3: Estimate Impact of Macrotrends on Surrogate Priorities

Step 3 evaluates the cumulative impact of one or more of 10 Macrotrends on each of the surrogate measures. (Table 11) and calculates a range of possible impacts on Virginia's transportation system performance for 2045. To account for interrelationships between Macrotrends, an order of influence is established to convey influence of one macrotrend on another. Order of influence ensures that the calculations respect the primary causal directions among Macrotrends, whereby Macrotrends that are early in the order of influence influence those that are later in the order of influence, but not typically the reverse.

Table 11: Order of Influence of Macrotrends and Influence of Macrotrends on Surrogate Calculations

Order of Influence	Macrotrend (listed in order of influence)	VMT Index	Shared Mobility Index	Safety Index	Number of Directional Miles of Roadways at Risk from Flooding	Tailpipe Emissions Index
1	Macrotrend # 1: Increase in Flooding Risk				•	
	Macrotrend # 9: Growth of the 65+ Cohort					
2	Macrotrend # 8: Increase in Workplace Flexibility	•				•
	Macrotrend # 2: Adoption of Highly Autonomous Vehicles	•		•		•
	Macrotrend # 3: Adoption of Electric Vehicles	•				•
3	Macrotrend # 4: Growth in Shared Mobility	•	•			•
4	Macrotrend # 5: Growth in E-commerce	•				•
	Macrotrend # 6: Greater Automation of Goods and Services	•				•
5	Macrotrend # 7: Growth of Professional Service Industry					
	Macrotrend # 10: Population and Employment Shift					
	Cumulative Impacts	•	•	•	•	•

• Quantified in Step 3

3.3.1. Impact of Step 1 Macrotrends on CTB GOAL A Surogate

Description: The total mileage traveled for all vehicles in the state, typically reported daily and analyzed over a 1-year period.

Significance: Vehicle miles traveled (VMT) is a key indicator of total transportation system usage, measuring vehicle travel demand. VMT estimates also provide a fundamental input for estimating needs in other indicators used as surrogates for CTB priorities, such as safety and tailpipe emissions. Estimates of future VMT changes are presented at the statewide and county level.

Data Sources:

- Share of jobs that are work-from-home capable: Dingel and Neiman[1]
- Share of jobs that are work-from-home capable: U.S. Bureau of Labor Statistics[2]
- Remote Work Survey: PricewaterhouseCoopers[3]
- Work-from-home Survey Report: Global Workplace Analytics[4]
- Virginia Industry Projections: Virginia Employment Commission[5]
- Employment Data: U.S. Census Bureau[6]
- Effect of AVs on Operating Cost and VMT: Compostella[7]
- Vehicle Cost Elasticities: Dong et al. (2012)[8]

[1] Dingel, Jonathan I., and Brent Neiman (2020). "How Many Jobs Can Be Done at Home?" Journal of Public Economics 189 (September 2020): 104235.

[2] Dey, Matthew, Harley Frazis, Mark A. Loewenstein, and Hugette Sun (2020). "Ability to Work from Home: Evidence from Two Surveys and Implications for the Labor Market in the COVID-19 Pandemic : Monthly Labor Review: U.S. Bureau of Labor Statistics." Accessed January 27, 2021.

[3] PricewaterhouseCoopers (2021). "Business Needs a Tighter Strategy for Remote Work." PwC. Accessed January 19, 2021.

[4] Global Workplace Analytics (2020). "Global Work-from-Home Experience Survey Report." May 2020.

[5] Virginia Employment Commission. "Industry Projections." Accessed February 1, 2021.

[6] U.S. Census Bureau. Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics (LODES).

[7] Compostella, Junia (2020). "Near- (2020) and Long-Term (2030-2035) Costs of Automated, Electrified, and Shared Mobility in the United States." Transport Policy, 2020, 14.

[8] Dong, Jing, Diane Davidson, Frank Southworth, and Tim Reuscher. "Analysis of Automobile Travel Demand Elasticities with Respect to Travel Cost." Oak Ridge National Laboratory, 2012.

- Virginia Daily Vehicle Miles Traveled: VDOT[1]
- Rate of return assumption of auto-based in-store purchases of retail trade: ATRI[2]
- Home delivery routes of e-commerce shipments stops per day: World Bank[3]
- Fare elasticity: Taiebat et al.[4] and Cohen et al.[5]
- Commute modes: FHWA[6]
- Percent non-work replacement VMT: Zhu and Mason[7]

Calculations:

Calculations to measure change in VMT in future year (2045) rely on outputs related to the following Macrotrends included in Section 3.1, Step 1. The impact of each calculated using order of influence (Table 12) as documented below. The Macrotrends' impact on VMT is estimated under the relevant headers before being combined to derive an overall range of estimates for VMT.

- Macrotrend # 2: Adoption of Highly Autonomous Vehicles
- Macrotrend # 3: Adoption of Electric Vehicles
- Macrotrend # 4: Growth in Shared Mobility
- Macrotrend # 5: Growth in E-commerce
- Macrotrend # 6: Greater Automation of Production and Services
- Macrotrend # 8: Increase in Workplace Flexibility

Table 12: VTrans Macrotrends Order of Influence

Order	Megatrend	Macrotrend
Independent	Climate Change	1. Increase in Flooding Risk
Independent	Socio-demographic Changes	2. Growth of the 65+ Cohort
1	Socio-demographic Changes	3. Increase in Workplace Flexibility
	Technological Advancements	4. Adoption of Highly Autonomous Vehicles
		5. Adoption of Electric Vehicles
		6. Growth in Shared Mobility
2	Evolving Consumption Patterns	7. Greater Automation of Goods and Services
		8. Growth in E-commerce
3	Socio-demographic Changes	9. Growth of Professional Service Industry
		10. Population and Employment Shift

[1] Virginia Department of Transportation. "2019 Traffic Data Daily Vehicle Miles Traveled."

[2] ATRI, E-Commerce impacts on the trucking industry, February 2019. Last accessed on April 8, 2021.

[3] The World Bank, Facilitating Trade and Logistics for E-Commerce: Building Blocks, Challenges and Ways Forward, December 2019. Last accessed on April 8, 2021.

[4] Taiebat, Morteza, Samuel Stolper, and Ming Xu (2019). "Forecasting the Impact of Connected and Automated Vehicles on Energy Use: A Microeconomic Study of Induced Travel and Energy Rebound." Applied Energy 247 (August 2019): 297–308.

[5] Cohen, Peter, Robert Hahn, Jonathan Hall, Steven Levitt, and Robert Metcalfe (2016). "Using Big Data to Estimate Consumer Surplus: The Case of Uber." Cambridge, MA: National Bureau of Economic Research, September 2016.

[6] Federal Highway Administration (2017). 2017 National Household Travel Survey.

[7] Zhu, P., & Mason, S. G. (2014). The impact of telecommuting on personal vehicle usage and environmental sustainability. *International Journal of Environmental Science and Technology,* 11(8), 2185-2200.

The combined impact of Macrotrend # 2: Adoption of Highly Autonomous Vehicles (AV), Macrotrend # 3: Adoption of Electric Vehicles, Macrotrend # 4: Growth in Shared Mobility (Ridesourcing only) on Vehicle Miles Traveled is calculated using the following steps.

1. Obtain change in total vehicle cost (accounts for fixed and variable costs) per mile for small and mid-size SUVs by vehicle type (unique combination of vehicle usage and fuel type) from Table A3 and A4 from Compostella et al.[1]

2. Given that total vehicle cost in calculation step # 1 has different impacts on personal usage vehicles and on ridesource vehicles, calculate two elasticities.
   – 2.1. Determine a change in travel demand elasticity of using an average of elasticities noted in various studies.[2]
   – 2.2. Determine a change in fare elasticity of using elasticities reported in Taiebat et al.[3] and Cohen et al. (2016).[4]

3. Utilizing outputs from calculation steps # 1 and # 2, calculate VMT change due to AV[5] for three scenarios (low, medium, high) using the following formula.[6]

4. $b_v = p_v \times e$

   Where:
   - *v* is a vehicle type *v* out of all vehicle types *V*.
   - b_v is the estimated VMT increase by vehicle type *v*.
   - p_v is the change in total vehicle cost by vehicle type (calculation step # 1)
   - *e* is the change in travel demand or fare elasticities (calculation step # 2)

5. Utilizing outputs from Section 3.1.4, VTrans Macrotrend # 4: Growth in Shared Mobility, estimate mix of personal-use and ridesource vehicles for three scenarios (low, medium, high). Retain ridesourcing VMT shares for low, medium, and high scenarios from Section 3.1.3, calculation step # 9. Convert to percentage of all VMT for each scenario by dividing by 2045 Virginia VMT calcuated in section 3.1.3 from StreetLight Data.

6. Utilizing outputs from Section 3.1.3, VTrans Macrotrend # 3: Adoption of Electric Vehicles, estimate vehicle fuel type (internal combustion engine, electric, and hybrid) for each of the personal-use and ridesource vehicle mix for all three scenarios (low, medium, high) derived from calculation step # 4. Retain internal combustion engine (ICE) vehicle, plug-in hybrid electric vehicle (PHEV), and electric vehicle (EV) Virginia fleet shares for the Business as Usual and Accelerated Electrification scenarios, which became the low and high scenarios respectively in this analysis. These fleet shares are from Section 3.1.3 calculation step # 1. ICE and EV Virginia fleet shares for the medium scenario are the average of the low and the high, and Virginia's medium scenario PHEV fleet share is set so that PHEV, ICE, and EV fleet shares add to 100%.

[1] Compostella, Junia, Lewis M. Fulton, Robert de Kleine, Chul Kim Hyung, and Timothy J. Wallington. "Near- (2020) and Long-Term Costs of Automated, Electrified, and Shared Mobility in the United States." Transport Policy, 2020, 14.

[2] Average demand elasticity calculated based on a review of the following studies: Hagemann, et al 2011 (Draft), Li, et al, 20112, Gillingham, 2010, Hymel , et al (2010), Karpus, 2010, Barla et al , 2009, Brand, 2009, McMullen & Zhang, 2008, Austin, 2008, Dargay, 2007, Small & Van Dender, 2007a, Small & Van Dender, 2007b, Feng et al, 2005, Goodwin, et al 2004*, Graham & Glaister 2002,2004*, de Jong & Gun, 2002* (shares), Brons, et al ,2002*, Goodwin , 2002*, Greene et al, 1999, TRACE, 1999 (Travel shares)*, Johannson & Shipper, 1997, Schimek, 1996a, Blundell et al, 2011, Souche, 2010, Bento et al, 2009, Salon (2009), Ingram and Liu, 1999, Small and Winston, 1999, Oum et al, 1992

[3] Taiebat, Morteza, Samuel Stolper, and Ming Xu. "Forecasting the Impact of Connected and Automated Vehicles on Energy Use: A Microeconomic Study of Induced Travel and Energy Rebound." Applied Energy 247 (August 2019): 297–308.

[4] Cohen, Peter, Robert Hahn, Jonathan Hall, Steven Levitt, and Robert Metcalfe. "Using Big Data to Estimate Consumer Surplus: The Case of Uber." Cambridge, MA: National Bureau of Economic Research, September 2016.

[5] Note that Compostella (2020) does not specifically call out levels of automation but uses the more generic term Automated Vehicles (AVs) which is typically used for higher levels of automation (level 3 and level 4)

[6] Note that VMT is inversely proportional to the cost and fare elasticities. A negative elasticity implies a unit decrease in price will lead to an increase in miles.

7. Estimate the VMT increase or *VMT change (d)* for personal-use and ridesource vehicles using the formula below:

   $c_v = b \times a_v$

   $MT\_2\_3\_4\ (d) = AV\ Market\ Penetration \times \sum_{v\,V} c_v$

   Where:

   - v is a vehicle type out of all vehicle types V.
   - a_v is the estimated share of fleet for vehicle type v.[1]
   - b is the estimated VMT increase from calculation step # 4.
   - c_v is the product of the share of fleet and VMT increase for vehicle type v.
   - *AV Market Penetration* is total market penetration percentages for vehicles with automation levels 3 or 4.

Impact of Macrotrend # 4: Growth in Shared Mobility (Micromobility only) on Vehicle Miles Traveled is calculated using the following steps.

8. Reduction in VMT due to increases in micromobility is estimated for each scenario (low, medium, high) using the following equation based on data from from Section 3.1.3, calculation step # 9.

   MT_4 = new 2045 micromobility mileage/2045 automobile VMT

   Where:

   - new 2045 micromobility mileage is the auto VMT that is expected to switch to micromobility by 2045. For the medium scenario, this is the micromobility switchable VMT for 2045 as calculated in step 1 for Macrotrend #4: Growth in Shared Mobility. Scenarios are defined such that 50% of the VMT that is expected to switch to micromobility in the medium scenario also switches in the low scenario, and 150% of the VMT that is expected to switch in the medium scenario also switches in the high scenario.

Impact of Macrotrend # 5: Growth in E-commerce on Vehicle Miles Traveled is calculated using the following steps.

Estimate annual automobile VMT avoided in future year (2045) due to e-commerce for each scenario (low, medium, high).

9. Determine the ratio between value per ton for B2C e-commerce commodity and value per ton for average goods-movement-dependent industry commodity at the state level. Use US BTS and FHWA's Freight Analysis Framework Version 5 (FAF5)[2] database, based on which the value per ton for "mixed freight" goods traveling within Virginia was estimated as $5,575 per ton, which was assumed to be a typical value per ton for retail trade or B2C e-commerce commodities. Using the same data, the overall value per ton of goods traveling to/from/within Virginia was estimated as $1,096 per ton. The value per ton ratio between retail trade or B2C e-commerce commodities and all goods movement dependent industry commodities was estimated as 5.1.

[1] To calculate the estimated fleet share for each vehicle type, combine retained ridesourcing VMT shares (calculation step # 5) and Virginia fleet shares (calculation step # 6) for low, medium, and high scenarios to estimate fleet share for the following vehicle types: private ICEV, private HEV, private PHEV40, private BEV200, private BEV300, ridesource ICEV, ridesource HEV, ridesource BEV200, and ridesource BEV300. BEV fleet shares are split evenly between 200- and 300-miles ranges.

[2] FHWA. Freight Analysis Framework Version 5.

10. Estimate future year (2045) non-commercial auto VMT avoided over base year (2019) at the Virginia MSA level.
    Auto VMT Avoided ^{Region}
    $= (Future\ B2C\ Output^{Region} \times Future\ B2C\ E\text{-}Com\ \%^{Region} - Base\ B2C\ Output\ \%^{Region} \times Base\ B2C\ E\text{-}Com\ \%^{Region}) \times (1+ARR) \times Value\ per\ Ton\ Ratio^{B2C\ E\text{-}Com} \times (1/AGVW) \times ATD^{Region}$

    Where:
    - *VMT Avoided* ^{Region}: Estimated regional daily auto VMT avoided by 2045 due to growth in B2C e-commerce
    - *ARR*: Rate of return assumption of auto-based in-store purchases of retail trade or B2C goods
    - *AGVW*: Auto average gross vehicle weight assumption
    - *ATD* ^{Region}: Average auto-based shopping travel distance assumption by region size

    According to an ATRI study,[1] around 8 percent of all in-store purchases are returned, hence the value of 8 percent was used as ARR. AGVW was assumed as 2.7 tons/vehicle. *ATD* ^{Region} was assumed as average shopping round-trip length by region size in Virginia based on the 2017 National Household Travel Survey.

11. Estimate annual automobile VMT avoided in future year (2045) due to e-commerce and e-commerce delivery methods for three scenarios (low, medium, high) using the following equation. Automobile VMT is avoided due to replacement of shopping trips with e-commerce.
    $\%\Delta\ Auto\ VMT = Daily\ 2045\ Auto\ VMT\ Avoided / Daily\ Auto\ 2019\ VMT \times 2019\ VMT / 2045\ VMT \times -1 \times (1 - Truck\ VMT\ Share)$

    Where:
    - *Daily Auto VMT Avoided* is the calculated number of automobile VMT avoided due to e-commerce, as calculated in calculation step # 11 above.
    - *Daily Auto VMT* is the 2019 number of daily auto VMT on Virginia roads as reported by VDOT.[2]
    - *2019 VMT* is the annual 2019 VMT estimated by StreetLight Data.
    - *2045 VMT* is the annual 2045 VMT estimated by StreetLight Data.
    - *Truck VMT Share* is the 2019 truck daily VMT share as reported by VDOT.[2]

Estimate annual additional truck VMT avoided in future year (2045) due to e-commerce.

12. Estimate future year (2045) Gross truck tons added over base year (2019) (due to cargo re-allocation from auto to truck) at the MSA level and Truck Class. Define MSAs by size:
    - Large MSAs: Richmond, Virginia Beach-Norfolk-Newport News and Northern Virginia
    - Medium MSAs: Charlottesville, Lynchburg, Roanoke
    - Rest of State: Small MSAs + Rural Areas

    $Gross\ Truck\ Tons\ Added_k^{Region} = (Future\ B2C\ Output^{Region} \times Future\ B2C\ E\text{-}Com\ \%^{Region} - Base\ B2C\ Output^{Region} \times Base\ B2C\ E\text{-}Com\ \%^{Region}) \times (1+TRR) \times Value\ per\ Ton\ Ratio^{B2C\ E\text{-}Com} \times T\ \%_k^{B2C\ E\text{-}Com}$

    Where:
    - $Gross\ Truck\ Tons\ Added_k^{Region}$: Estimated 2045 regional daily gross truck tons added by 2045 for truck type k due to growth in B2C e-commerce
    - *Future B2C Output* ^{Region}: Output of calculation Steps 17-19 for 3.1.5. VTrans Macrotrend #5: Growth in E-commerce
    - *Base B2C Output* ^{Region}: Output of calculation Steps 17-19 for 3.1.5. VTrans Macrotrend #5: Growth in E-commerce
    - *Future B2C E-Com %* ^{Region}: Output of calculation steps 6-9 for 3.1.5. VTrans Macrotrend #5: Growth in E-commerce
    - *Base B2C E-Com %* ^{Region}: Output of calculation steps 6-9 for 3.1.5. VTrans Macrotrend #5: Growth in E-commerce
    - *TRR*: Rate of return assumption of truck-based retail trade or B2C e-commerce goods

[1] ATRI, E-Commerce impacts on the trucking industry, February 2019, Available at: https://truckingresearch.org/wp-content/uploads/2019/02/ATRI-Impacts-of-E-Commerce-on-Trucking-02-2019.pdf (last accessed on April 8, 2021)

[2] Virginia Department of Transportation (2019). Traffic Data Daily Vehicle Miles Traveled. 20 – DVMT by Federal Vehicle Class 2019. Accessed May 25, 2021.

- *Value per Ton Ratio*$^{B2C\ E\text{-}Com}$: Output of calculation step 9 above
- $T\ \%_k^{B2C\ E\text{-}Com}$: Truck tonnage share for truck type k assumption used in retail trade or B2C e-commerce goods

According to an ATRI study,[1] between 13 and 30 percent of all online orders result are returned, hence an average value of 22 percent was assumed as TRR. Depending on the size of the region, different truck class distributions, $T\ \%_k^{B2C\ E\text{-}Com}$, were assumed for retail trade or B2C e-commerce goods

13. For each scenario (low, medium, high), the following equation is used to estimate the increase in truck VMT in the future year (2045) due to growth in e-commerce accounting for commercial drone delivery services.
$\%\Delta\ Truck\ VMT = \%\Delta\ Truck\ VMT_c \times Truck\ VMT\ Share$

Where:
- $\%\Delta\ Truck\ VMT$ is the change in the share of truck VMT incurred due to e-commerce after accounting for commercial drone delivery service, from calculation step # 12.
- *Truck VMT Share* is the 2019 truck daily VMT share as reported by VDOT.[2]
- *c* represents the geographic level being analyzed

14. Estimate future year (2045) Truck VMT added over Baseline by Virginia MSAs and Truck Class
$Truck\ VMT\ Added_k^{Region} = Gross\ Truck\ Tons\ Added_k^{Region} \times [(T\ \%_k^{B2C\ E\text{-}Com})\ /\ \sum_k (TGVW_k \times T\ \%_k^{B2C\ E\text{-}Com})] \times TTD^{\ Region}$

Where:
- $Truck\ VMT\ Added_k^{Region}$: Estimated regional daily truck VMT added by 2045 for truck type k due to growth in B2C e-commerce
- $TGVW_k$: Truck average gross vehicle weight assumption for truck type *k*
- $TTD^{\ Region}$: Average truck travel distance per unit B2C e-commerce shipment assumption by region size

$TGVW_k$ for truck classes used in B2C e-commerce are as shown in Table 13.

Table 13: B2C E-Commerce related Average Gross Vehicle Weight by Truck Class

Truck Class	Average Gross Vehicle Weight (tons/vehicle)
Class 6/7 Urban Delivery	14.8
Class 4/5 Urban Delivery	9.3
Class 3 Walk-in/Delivery	6.0
Class 2b Van	4.0
Other Modes (Passenger Cars, Bike, Trike, Walk, etc.)	2.7

According to a World Bank Report,[3] home delivery routes of e-commerce shipments typically consist of 50 to 150 stops per day, depending on the type of vehicle. $TTD^{\ Region}$ was calculated using an equation and assumptions as follows:
$TTD\ Region = 30{,}000\ miles\ traveled\ per\ year\ /\ 300\ days\ per\ year\ /\ Stops\ per\ day^{Region}$

Where:
- $Stops\ per\ day^{Region}$: Number of stops made per day by a truck for B2C e-commerce delivery was assumed to vary by region size: 100 stops for large MSA, 50 for medium size MSA and 25 for rest of the State.

[1] ATRI, E-Commerce impacts on the trucking industry, February 2019, Available at: https://truckingresearch.org/wp-content/uploads/2019/02/ATRI-Impacts-of-E-Commerce-on-Trucking-02-2019.pdf (last accessed on April 8, 2021)

[2] Virginia Department of Transportation (2019). Traffic Data Daily Vehicle Miles Traveled. 20 – DVMT by Federal Vehicle Class 2019. Accessed May 25, 2021.

[3] The World Bank, Facilitating Trade and Logistics for E-Commerce: Building Blocks, Challenges and Ways Forward, December 2019. Available at: https://openknowledge.worldbank.org/bitstream/handle/10986/33174/Facilitating-Trade-and-Logistics-for-E-Commerce-Building-Blocks-Challenges-and-Ways-Forward.pdf (last accessed on April 8, 2021)

Impact of Macrotrend # 6: Greater Automation of Production and Services on Vehicle Miles Traveled is calculated using the following steps.

Estimate Truck VMT added over base year (2019) by Truck Class for Virginia MSA's and rural areas for future year (2045) for each scenario (low, medium, high).

15. $\textit{Truck VMT Change}_k^{Region} = \textit{Gross Truck Tons Change}_k^{Region} \times (\textit{Baseline Gross Truck VMT}_k^{Region}) / (\textit{Baseline Gross Truck Tons}_k^{Region})$

    Where:

    - $\textit{Truck VMT Change}_k^{Region}$: Estimated regional daily truck VMT added over base year (2019) by 2045 for truck type k due to growth in 3D printing
    - $\textit{Gross Truck Tons Change}_k^{Region}$: Output of calculation step 14 for 3.1.6. VTrans Macrotrend #6: Greater Automation of Production and Services
    - $\textit{Baseline Gross Truck VMT}_k^{Region}$: Total gross truck tons (Baseline) for Large and Medium MSAs and Rest of State (Small MSAs + Rural Areas) and Truck Class
    - $\textit{Baseline Gross Truck Tons}_k^{Region}$: Total truck VMT (Baseline) for Large and Medium MSAs and Rest of State (Small MSAs + Rural Areas) and Truck Class

Table 14: 3D Printing-related Daily Truck VMT Change by Truck Type, 2045

Truck Type	2045 Daily Gross Truck Tons (000s) Change Over Base Year (2019)		
	Low Estimate	Medium Estimate	High Estimate
Class 8 Tractor Long-Haul	-47.1	-363.4	-649.6
Class 8 Tractor Short-Haul	2.8	21.9	39.1
Class 8 Tractor Drayage	-4.8	-37.0	-66.1
Class 6/7 Regional Haul	27.3	211.0	377.3
TOTAL	-21.7	-167.4	-299.3

Table 15: 3D Printing-related Daily Truck VMT Change by Region, 2045

Region	2045 Daily Gross Truck Tons (000s) Change Over Base Year (2019)		
	Low Estimate	Medium Estimate	High Estimate
Charlottesville, VA	-0.2	-1.7	-3.0
Lynchburg, VA	0.0	0.3	0.6
Roanoke, VA	-1.8	-14.3	-25.5
Richmond, VA	-1.3	-9.7	-17.3
Virginia Beach-Norfolk-Newport News, VA-NC	-4.6	-35.9	-64.2
Northern Virginia, VA	-1.0	-7.9	-14.1
Rest of State	-12.7	-98.3	-175.7
TOTAL	-21.7	-167.4	-299.3

For each scenario, estimate the change in truck VMT due production automation including 3D printing.

$MT\_6 = \% \text{ Truck } VMT_c \times \text{Truck VMT Share}$

Where:

- *% Truck VMT* is the change in the share of truck VMT incurred due to production automation and 3D printing, as calculated in step 1 for Macrotrend # 6: Greater Automation of Goods and Services.
- *Truck VMT Share* is the 2019 truck daily VMT share as reported by VDOT.
- *c* represents the geographic level being analyzed

Estimate the increase in truck VMT in the future year (2045) due to growth in e-commerce accounting for commercial drone delivery services.

$\text{Truck VMT Avoided}_k^{Region} = \text{Gross Truck Tons Avoided}_k^{Region} \times (1 / TGVW_k) \times TTD^{Region}$

Where:

- $\text{Truck VMT Avoided}_k^{Region}$: Estimated regional daily truck VMT avoided by 2045 for Class 2b van due to growth in short-range drone delivery service
- $TGVW_k$: Truck average gross vehicle weight assumption for Class 2b van
- TTD^{Region}: Average truck travel distance per unit short-range drone shipment assumption by region size
- *TGVW* for Class 2b van used in short-range drone suited shipments is assumed as 4.0 tons/vehicle

$\% \text{ VMT} = \% \text{ Truck VMT} \times \text{Truck VMT Share}$

Where:

- *% Truck VMT* is the change in the share of truck VMT incurred due to e-commerce after accounting for commercial drone delivery service, as calculated in step 13 above.
- *Truck VMT Share* is the 2019 truck daily VMT share as reported by VDOT.[1]

16. For each scenario, estimate the change in 2045 truck VMT due to greater automation of production and services.

    $MT\_6 = \%\Delta \text{ Truck VMT} \times \text{Truck VMT Share}$

    Where:

    - *%Δ Truck VMT* is the change in the share of truck VMT incurred due to production automation and 3D printing, as calculated in Calculation Step 15 above.
    - *Truck VMT Share* is the 2019 truck daily VMT share as reported by VDOT.[2]

Impact of VTrans Macrotrend # 8: Increase in Workplace Flexibility on Vehicle Miles traveled is calculated using the following steps.[3]

[1] Virginia Department of Transportation (2019). Traffic Data Daily Vehicle Miles Traveled. 220 – DVMT by Federal Vehicle Class 2019. Accessed May 25, 2021.

[2] Virginia Department of Transportation (2019). Traffic Data Daily Vehicle Miles Traveled. 220 – DVMT by Federal Vehicle Class 2019. Accessed May 25, 2021.

[3] Assumptions:

- Distribution of commute mode is the same for all North American Industry Classification System (NAICS) occupations.
- Morning peak period average trip length is the same for all trip type (e.g., HBW, HBO, NHB) because it is not split out by mode purpose in available datasets.
- Zero carpooling is assumed.
- The peak AM period is defined as 6AM to 9PM.
- VMT is assigned to the county where the trip ends.
- Discount factor is the percent increase in non-work VMT by telecommuters compared to non-telecommuters with respect to non-telecommuters' daily work VMT from the 2009 NHTS, as reported by Zhu & Mason (2014).

17. Calculate number of workers by industry for each county in Virginia.
    $\# \text{ of workers}_{2045} = \# \text{ of workers}_{2018} \times \text{projected industry growth rate}$

    Where:
    - *# of workers*$_{2018}$ is the number of workers at the two-digit NAICS industry level in the base year (2018)[1]
    - *projected industry growth rate* is the growth rate by 2-digit NAICS codes[2]

18. Utilize the following formula to calculate WF capacity in the future year (2045).
    $\text{WF capacity count} = \sum_{i=industry} \%\text{WF Capable Jobs}_i \times \#\text{of workers}_i$

    Where:
    - *%WF Capable Jobs*$_i$ is the share of workplace flexible jobs in industry i,as calculated in Section 3.1.7.

    × *#of workers*$_i$ is the number of workers in industry i, as calculated in Section 3.1.7.

19. Calculate number of home-based commute round trips reduced due to VTrans Macrotrend # 8: Increase in Workplace Flexibility for three scenarios[3,4]: Low (2-days remote work), medium (3.5-days remote work), and high (5-days remote work) in the future year (2045).

20. Convert reduction in home-based commute round trips to VMT reduction in the base year (2019) due to VTrans Macrotrend # 8: Increase in Workplace Flexibility for AM peak hours for each scenario (low, medium, high).
    $\text{VMT reduction rate}_c = \text{trip ends}_c \times \%\text{HBW}_c - \text{reductPotential} \times \%\text{autoCommute} \times \%\text{AM Peak}_c \times \text{avg trip length}_c \times (1 - \text{discount factor}) \times 2$

    Where:
    - *trip ends*$_c$ if the number of vehicle trips per county *c* during the morning peak period[5]
    - *%HBW*$_c$ is the percent of trips per county *c* that are home-based work (HBW)[6]
    - *reductPotential* is the output of calculation step # 20.
    - *%autoCommute* is the share of workers that use private automobile as primary mode to workplaces in Virginia (91.43%).[7]
    - *%AM Peak*$_c$ is the percent of StreetLight Data trips per county in peak morning peak period on weekdays (Mon-Thurs in 2019).[8]
    - *avg trip length*$_c$ is the average trip length in miles (assigned to destination by county).[9]
    - *discount factor* is the percent non-work replacement VMT (discount factor)[10]

[1] US Census Bureau. Longitudinal Employer-Household Dynamics

[2] Virginia Employment Commission. "Industry Projections." Accessed February 1, 2021.

[3] PricewaterhouseCoopers. "Business Needs a Tighter Strategy for Remote Work." PwC. Accessed January 19, 2021.

[4] Global Workplace Analytics and flexjobs. "2017 State of Telecommuting in the U.S. Employee Workforce," 2017.

[5] Streetlight Data

[6] Streetlight Data

[7] Federal Highway Administration 2017 National Household Travel Survey.

[8] Streetlight Data

[9] Streetlight Data

[10] Zhu, P., & Mason, S. G. (2014). The impact of telecommuting on personal vehicle usage and environmental sustainability. *International Journal of Environmental Science and Technology,* 11(8), 2185-2200.

21. Calculate annualized VMT reduction using the following formula: VMT reduction was annualized by multiplying by 261 workdays per year. The total can be multiplied by 2 to account for both morning and evening peak periods.
MT_7 = *VMT reduction rate*$_c$ *x Number of Annual Weekdays x Number of Daily Weekday Peak Periods*

Where:
- *Annualized VMT reduction*$_c$ is the estimated reduction in VMT over a calendar year for each subgeography *c*
- *VMT reduction rate*$_c$ is the output from calculation step # 21
- *Number of Annual Weekdays* equals 261 weekdays in a calendar year
- *Number of Daily Weekday Peak Periods* is estimated two (morning and afternoon) peak periods on a typical weekday

Calculate the combined effect of the Macrotrends on vehicle miles traveled.

22. Combine the independent effects of each macrotrend on VMT (calculation steps # 6, # 7, and # 15, and # 22) by multiplying the independent effects of each macrotrend using the following equation:

$$Total\ Impact_{VMT} = VMT_{start} \times (1 + MT_7) \times (1 + MT_{2\ 3\ 4}) \times (1 + MT_5) \times (1 + MT_6) \times (1 + MT_4)$$

Step 3: Impact of VTrans Macrotrends on CTB Goal A in the Year 2045

The results of calculation step # 23 are included in Table 16 and should be interpreted as follows:

- **Low-impact Scenario:** Number of vehicle miles traveled in Virginia is estimated to increase by 4% over the 2045 no-build scenario (absence of VTrans Macrotrends (Step 1)).
- **Medium-impact Scenario:** Number of vehicle miles traveled in Virginia is estimated to increase by 8% over the 2045 no-build scenario (absence of VTrans Macrotrends (Step 1)).
- **High-impact Scenario:** Number of vehicle miles traveled in Virginia is estimated to increase by 17% over the 2045 no-build scenario (absence of VTrans Macrotrends (Step 1)).

Table 16: Estimated Impact of VTrans Macrotrends on CTB Goal A in Year 2045

CTB Goal	Surrogate for CTB Goal	Low Estimate	Medium Estimate	High Estimate
Goal A: Economic Competitiveness and Prosperity	Vehicle Miles Traveled (VMT) Index	1.04	1.08	1.17

Where 1.0 is 2045 business-as-usual scenario where VTrans Macrotrends have no impacts.

3.3.2. Impact of Step 1 Macrotrends on CTB GOAL B Surogate

Description: Share of Urban Area Single-Occupant-Vehicle VMT switchable to shared mobility

Significance: A change in the share of trips switchable to shared mobility can indicate progress toward attaining CTB Goal B: Accessible and Connected Places

Data Sources:

- Percentage of VMT switchable to TNC at the statewide level and the county level[1]
- Percentage of VMT switchable to micromobility at the statewide level and the county level[2]

Calculations:

Calculations to measure change in share of VMT switchable to shared mobility in future year (2045) rely on outputs related to the following macrotrends included in Section 3.1, Step 1. The calculation relative to the baseline is as follows.

Mode Share Surrogate Measure= 1 + *a x (% VMT Switchable to TNC + % VMT Switchable to Micromobility)*

Where:
a = 0.5 ➔ low scenario; a = 1 ➔ medium scenario; a = 1.5 ➔ high scenario

[1] See Section 3.4, Step 9 (page 25 of this document)

[2] See Section 3.4, Step 9 (page 25 of this document)

Step 3: Impact of VTrans Macrotrends on CTB Goal B in Year 2045

The results of the change in share of VMT switchable to shared mobility calculations are included in Table 17. Statewide results should be interpreted as follows:

- Low estimate: The change in share of VMT switchable to shared mobility is estimated to be 9% higher than the 2045 no-build scenario.
- Medium estimate: The change in share of VMT switchable to shared mobility is estimated to be 18% higher than the 2045 no-build scenario
- High estimate: The change in share of VMT switchable to shared mobility is estimated to be 27% higher than the 2045 no-build scenario

Table 17: Change in share of VMT switchable to shared mobility

Metric	Low Estimate	Medium Estimate	High Estimate
Shared Mobility Index	1.09	1.18	1.27

Due to the lack of reliable available and applicable research, the method does not account for the following factors.

- Changes in walking, bicycling, carpooling/average vehicle occupancy, or transit usage.
- Shared mobility beyond micromobility and ridesourcing.
- Changes in energy prices.
- Public or private investment into transportation infrastructure or technologies.

3.3.3. Impact of Step 1 Macrotrends on CTB GOAL C Surogate

Description: As outlined in Section 3.2, estimated change in number of crashes involving fatalities and serious injuries is used as a surrogate to assess impact of VTrans Macrotrends on CTB Goal C: Proactive System Management.

Significance: A change in the number of crashes involving fatalities and serious injuries can impact CTB Goal C which has an objective of reducing the number of fatalities and serious injuries.

Data Sources:

- Crash modification factors associated with AV technologies: Li and Kockelman[1]
- Crash statistics for Virginia: VDOT[2]
- Number of fatal and serious injury crashes in Virginia: FHWA[3]
- Adoption of AV technologies between levels 1 and 4: Bansal and Kockelman[4]
- Safety benefit to market penetration of AVs: Marler et al. (2018)[5]

Calculations:

Calculations to measure change in the number of crashes involving fatalities and serious injuries in future year (2045) rely on outputs related to the following macrotrends included in Section 3.1, Step 1. The Macrotrend's impact on safety along with the impact of changing VMT calculated in Section 3.3.1 are estimated in this section under the relevant headers before being combined to derive an overall range of estimates for safety changes.

- Macrotrend # 2: Adoption of Highly Autonomous Vehicles

[1] Li, T., & Kockelman, K. M. (2016, January). Valuing the safety benefits of connected and automated vehicle technologies. In Transportation Research Board 95th Annual Meeting (Vol. 1).

[2] Virginia Department of Transportation (2019). Virginia Crashes.

[3] Federal Highway Administration (2019). State Highway Safety Report (2019) – Virginia.

[4] Bansal, P., & Kockelman, K. M. (2017). Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies. Transportation Research Part A: Policy and Practice, 95, 49-63.

[5] Marler, S., Hofer, B., Sharp, W., & Markt, J. (2018). Interstate 80 Automated Corridor (No. 18-04176).

Impact of Macrotrend # 2: Adoption of Highly Autonomous Vehicles Number of Crashes Involving Fatalities and Serious Injuries is calculated using the following steps:

1. Utilize estimated market penetration[1] of automation (Vehicle Automation Levels 1 through 4) for "low impact", "medium impact", and "high impact" scenarios for 2045 VTrans Macrotrend # 2: Adoption of Highly Autonomous Vehicles.

2. Utilize Table 2 in Li and Kockleman[3] to establish a crosswalk between vehicle automation features (e.g. Forward Collision Warning or FCW) and vehicle collision type (e.g. rear end).

3. Create three different scenarios based on three different mixes of vehicle automation. Utilize market penetration of Level 4 vehicles (Table 19) to estimate the remaining penetration with Levels 1 and 2, keeping overall automation at 90%.

Table 19: Scaled Market Penetration of Highly Automated Vehicles by Vehicle Automation Levels

	Low Estimate[4]	Medium Estimate[5]	High Estimate[6]
Assumed Market Penetration of Vehicles with Level 1 through 4 technologies[7]	90%	90%	90%
Level 4 (calculation step # 1, Table 4)	25%	45%	87%
Remaining Vehicles with Levels 1 and 2 Technologies only	65%	45%	3%

[1] Assumption: The maximum market share is taken rather than the sum because many vehicles are expected to be equipped with multiple automation technologies.

[2] Bansal, P., & Kockelman, K. M. (2017). Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies. Transportation Research Part A: Policy and Practice, 95, 49-63.

[3] Li, T., & Kockelman, K. M. (2016, January). Valuing the safety benefits of connected and automated vehicle technologies. In Transportation Research Board 95th Annual Meeting (Vol. 1).

[4] Corresponds to "conservative" scenario (More ADAS and less ADS in fleet) in Li and Kockleman. The split across vehicle automation levels is assumed to account for more ADAS and less ADS such that the total total market share of vehicles with some level of automation is at 90%, consistent with Li and Kockelman.

[5] Corresponds to "moderate" scenario (Middle of road ADAS and ADS in fleet) in Li and Kockleman. The equal distribution of across ADAS and ADS such that the total total market share of vehicles with some level of automation is at 90%, consistent with Li and Kockelman.

[6] Corresponds to" aggressive" scenario (More ADS than ADAS in fleet) in Li and Kockleman. The split across vehicle automation levels is assumed to account for less ADAS and almost entirety with ADS such that the total total market share of vehicles with some level of automation is at 90%, consistent with Li and Kockelman.

[7] Li, T., and Kockelan, K,., *Valuing the Safety Benefits for Connected and Automated Vehicle Technologies*, In Transportation Research Board 95th Annual Meeting (Vol. 1).

4. Utilize the crash modification factors (CMFs) reported in Li and Kockleman[1] using the KABCO Scale to derive crash modification factors by scenario (Table 20).

Table 20: Crash Modification Factors due to Vehicle Automation

Crash Severity	Crash Modification Factors by Scenario		
	Low Estimate	Medium Estimate	High Estimate
Fatal Injury – K	45%	51%	63%
Severe Injury – A	56%	62%	74%
Visible Injury – B	70%	74%	84%
Non Visible Injury – C	79%	81%	87%
Property Damage Only – O	81%	83%	87%

5. Utilize crash modification factors (CMF) from Table 3 in Li and Kockleman[4] to calculate expected number of crashes using the following formula:
   $EC_s^c = RC_s^c \times CMF$

   Where:
   - EC_s^c is the number of expected crashes by collision type c[5] and severity type s[6] from Calculation Step # 4
   - RC_s^c is the number of reported VDOT crashes by collision type c and severity s in 2019
   - *CMF* is the crash modification factor by scenario

6. Calculate number of expected crashes by collision severity using the following formula:
   $EC^s = \sum_{(c=1)}^{C} EC_s^c$

   Where:
   - EC^s is the expected number of crashes summed across the severity types
   - EC_s^c is the expected number of crashes by collision type c and severity type s

7. Calculate crash reduction rate for the three scenarios (low, medium, high) using the formula below:
   $Crash\ Reduction\ Rate^s = EC^s/RC^s$

   Where:
   - EC^s is the expected number of crashes summed across the severity type *s*
   - $Crash\ Reduction\ Rate^s$ is the crash reduction rate by collision severity type *s*
   - *RC* is reported VDOT crashes by severity type *s*

[1] Li, T., and Kockelan, K,., *Valuing the Safety Benefits for Connected and Automated Vehicle Technologies*, In Transportation Research Board 95th Annual Meeting
(Vol. 1).

[4] Li, T., & Kockelman, K. M. (2016, January). Valuing the safety benefits of connected and automated vehicle technologies. In Transportation Research Board 95th Annual Meeting (Vol. 1).

[5] Table 2 in Li, T., and Kockelan, K,., *Valuing the Safety Benefits for Connected and Automated Vehicle Technologies*, In Transportation Research Board 95th Annual Meeting (Vol. 1).

[6] KABCO Scale

8. Assuming a linear relation of safety benefit to the market penetration of AVs from Marler et al,[1] estimate crash reduction by crash severity based on AV market penetration in Table 21 and the expected crash reduction rate in step #5.

9. Interpolate crash reductions corresponding with the low, medium, and high estimates of AV market penetration.

   potential crash rate reduction = lower crash red + (upper crash red – lower crash red/upper market pen – lower market pen) × (market pen – lower market pen)

   Where:
   - *lower crash red* and *upper crash red* are respectively the lower and upper crash rate reductions between which the actual crash reduction is being interpolated.
   - *lower market pen* and *upper market pen* are respectively the lower and upper market penetrations corresponding with the lower and upper crash reductions.
   - *market pen* is the AV market penetration for which the potential crash reduction is being interpolated.

Table 21: Potential Crash Rate Reductions by AV Market Penetration

Crash Rate Reduction	Low Estimate	Medium Estimate	High Estimate
Fatal Injury - K	23%	38%	62%
Severe Injury - A	29%	43%	73%
Moderate Injury - B	36%	56%	83%
Minor Injury - C	41%	62%	85%
Property Damage Only - O	42%	63%	86%

Estimate the impact of change in vehicle miles traveled (2045) derived from Section 3.3.1 on safety

10. Account for ΔVMT (2045). Estimated crashes compared with baseline are calculated for each 'KABCO' crash severity level and the low, medium, and high scenarios by multiplying the forecasted "low," "medium," and "high" VMT growth from Section 3.3.1 by the potential crash rate reductions, as shown in the equation below. Combine remaining crash values compared to baseline values for crash types K and A.

    crashes compared to baseline = ΔVMT × (1–potential crash rate reductions)

    Where:
    - *ΔVMT* is the change in VMT calculated for the low, medium, and high scenarios in Section 3.3.1 calculation step # 23 and shown in Table 22.
    - *potential crash rate reductions* is the estimate for the change in crash rate shown in the calculation step # 9, Table 21.

Table 22: VMT Increases Compared to Baseline by Scenario

Low Estimate	Medium Estimate	High Estimate
4%	8%	17%

[1] Marler, S., Hofer, B., Sharp, W., & Markt, J. (2018). *Interstate 80 Automated Corridor* (No. 18-04176).

Table 23: Crashes Compared to Baseline by Scenario

Crashes	Low Estimate	Medium Estimate	High Estimate
Fatal Injury - K	80%	66%	44%
Severe Injury - A	74%	62%	31%
Visible Injury - B	66%	47%	20%
Non Visible Injury - C	62%	41%	17%
Property Damage Only - O	60%	40%	16%

11. Make a weighted safety index based on the proportional split in Virginia between K and A crashes using 2019 5-year average crash counts.[1] For the statewide analysis, this translates to the following weights: 9.4% (K) and 90.6% (A).

    ∆SafetyIndex (2045)= K crashes × (K counts)/(K counts + A counts) + A crashes × (A counts)/(K counts + A counts)

    Where:

    - *K crashes* is the estimated fatal crashes compared with baseline shown in the table above ("crashes compared to baseline" from calculation step # 10).
    - *A crashes* is the estimated serious injury crashes compared with baseline shown in the table above ("crashes compared to baseline" from calculation step # 10).
    - *K counts* is the 2019 5-year fatal injury crash count in Virginia.[2]
    - *A counts* is the 2019 5-year serious injury crash count in Virginia.[3]

Step 3: Impact of VTrans Macrotrends on CTB Goal C in the Year 2045

The results of calculation step # 11 for the statewide analysis are included in Table 24 and should be interpreted as follows:

- Low-impact Scenario: Number of crashes involving fatalities and serious injuries is estimated to decrease by 26% over the 2045 no-build scenario (absence of VTrans Macrotrends (Step 1))
- Medium-impact Scenario: Number of crashes involving fatalities and serious injuries is estimated to decrease by 38% over the 2045 no-build scenario (absence of VTrans Macrotrends (Step 1))
- High-impact scenario: Number of crashes involving fatalities and serious injuries is estimated to decrease by 67% over the 2045 no-build scenario (absence of VTrans Macrotrends (Step 1))

Tabe 24: Estimated Impact of VTrans Macrotrends on CTB Goal C in Year 2045

CTB Goal	Surrogate for CTB Goal	Low Estimate	Medium Estimate	High Estimate
Goal C: Safety for All Users	Safety Index (Estimated Change in Number of Crashes with Fatalities + Serious Injuries Due to VTrans Macrotrends)	0.74	0.62	0.33

Where 1.0 is 2045 business-as-usual scenario where VTrans Macrotrends have no impact.

[1] Federal Highway Administration (2019). State Highway Safety Report (2019) – Virginia. Accessed June 24, 2021.
[2] Federal Highway Administration (2019). State Highway Safety Report (2019) – Virginia. Accessed June 24, 2021.
[3] Federal Highway Administration (2019). State Highway Safety Report (2019) – Virginia. Accessed June 24, 2021.

Limitations and Opportunities for Continuous Improvement

There are several known and unknown uncertainties as well as limitations of the method described above. Some of the known uncertainties and limitations include:

- Uncertainties around baseline assumptions not captured since the outputs are over the 2045 no-build scenario which assume absence of VTrans Macrotrends. Therefore, this method does not capture the impacts of ongoing education and awareness campaigns and physical infrastructure improvements.
- Statewide perspective conceals localized performance impacts. For example, market penetration of vehicle automation level 4 technologies could be unevenly distributed across Virginia likely resulting in uneven realization in the safety benefits.
- Effects of alternative population growth and migration patterns that impact VMT and therefore safety estimations are not considered.
- Change in pedestrian or bicycle exposure to collisions is not considered. For example, propensity to walk and bike, among other factors, could change exposure of pedestrians and bicyclists.
- Future changes in vehicle composition (size, speed, acceleration, deceleration characteristics) are not considered.
- This method does not account for mode shift or differentiation of relative VMT change of personal and commercial vehicles.

3.3.4. Impact of Step 1 Macrotrends on CTB GOAL D Surogate

Description: For the purposes of calculations, this is defined as increase in flooding risk due to: (1) sea level rise; (2) storm surge; and, (3) inland and riverine flooding.

Data Sources:

Data sources for calculating flooding risk or measuring transportation system vulnerability to flooding are listed in Table 25 by hazard type:

Table 25: Data Sources by Scenario for Estimating Risk from Flooding Events

Hazard	Data Source of Projected Hazard	Scenario 1	Scenario 2	Scenario 3
Sea Level Rise	Virginia Institute of Marine Sciences (VIMS)	Intermediate sea level rise scenario (Year 2040)	Intermediate-High sea level rise scenario (Year 2040)	Extreme sea level rise scenario (Year 2040)
Storm Surge	National Hurricane Center (NHC)	Category 2 hurricane storm surge	Category 3 hurricane storm surge	Category 4 hurricane storm surge
Inland/Riverine Flooding	Federal Emergency Management Agency (FEMA) VDOT	100-year flood zone AND Historical Weather-Related Damages or Closures	500-yr flood zone AND Historical Weather-Related Damages or Closures	FEMA 500-yr flood zone with varying width buffer (10-200ft) based on floodplain width AND Historical Weather-Related Damages or Closures (Appendix 1-F)

Calculations:

Please refer to Appendix 1 for more description of methods and calculations.

Step 3: Impact of VTrans Macrotrends on CTB Goal C in Year 2045

The impact of VTrans Macrotrends

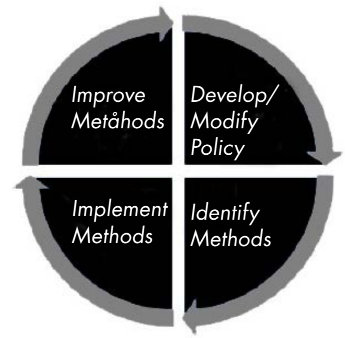
Table 26: Estimated Impact of VTrans Macrotrends on CTB Goal D in Year 2045[1]

CTB Goal	Surrogate for CTB Goal	Low Estimate	Medium Estimate	High Estimate
Goal D: Proactive System Management	Number of Directional Miles at Risk from Flooding (in miles) by Hazard	SLR - 935 SS - 7,706 IRF - 17,475	SLR - 1,101 SS - 13,095 IRF - 17,829	SLR - 1,424 SS - 17,092 IRF - 18,250

Limitations and Opportunities for Continuous Improvement

The execution of the methodology outlined in this technical memorandum relies on data and computations to ensure transparent, data-driven, and replicable methods. The following should be noted:

Figure 4: Opportunities for Continuous Improvement



- **Data:** The execution relies on data from state and national sources. Each of these sources relies on various methods, techniques, and technologies to develop its datasets and, therefore, has its own limitations such as:
  - Lack of readily usable data: There are instances in which the current completeness and accuracy of datasets makes it unsuitable used to execute the methodology outlined in this technical memorandum. For example, more information on roadway horizontal and vertical geometry will significantly improve quality and accuracy of the vulnerability assessment results. Similarly, availability of alternative routes will help provide more relevant data to determine the Adaptive Capacity of a facility (more details in Section 2) and thereby improve accuracy of the VTrans Vulnerability Assessment. Therefore, application of transportation planning or engineering judgment is recommended prior to developing solutions.
  - Scope of the task: The availability of data largely governed the scope of the task. For example, more precise information on transit and rail assets can help make the VTrans Vulnerability Assessment more multimodal in nature.
- **Computations:** The sheer size and magnitude of the effort relies on complex computations to perform an analysis on more than one million roadway segments. The effort requires synthesis, format conversions, and computations, such as in the following examples, that could result in inadvertent errors.
  - Units: Different data sources have different units. Some datasets are available by directional segment, whereas other datasets are available at the area or sub-area level.
  - Levels of aggregations: Some datasets are more aggregated than others. For example, historical weather data are available as point data and were aggregated and assigned to roadway segments (See Appendix 1-F).
  - Frequency of data collection: Some datasets are collected in real time, whereas other datasets are updated once per year or even less frequently.
  - Frequency of data reporting: In addition to the variations in data collection schedule, some datasets are reported in real time, where other datasets are reported once a year.
  - Data formats: Transportation assets are currently available in vector formats primarily as line or points features where weather related datasets are primarily in raster formats. One of the significant limitations of vector formats is that they are not ideal for data on continuous scales such as those available for weather, precipitation, etc. This limitation results in less accuracy (refer to Appendix 1-E) and should be a higher priority for any future work.

The Statewide Transportation Planning Team at OIPI sees these considerations as opportunities for continuous improvement. Methods and techniques outlined in this memorandum can continue to evolve and improve based on advances in technology, data quality, data collection, and reporting tools.

[1] SLR: Sea level rise; SS: Storm surge; IRF: Inland and riverine flooding

3.3.5. Impact of Step 1 Macrotrends on CTB GOAL E Surogate

Description: As outlined in Section 3.2, estimated change in tailpipe emissions for the future year (2045) is used as the surrogate to assess the impact of the VTrans Macrotrends (outlined in Section 3.1) on CTB Goal E: Healthy Communities and Sustainable Transportation Communities.

Significance: Air pollution from transportation, such as from particulate matter, nitrogen oxide, volatile organic compounds, and greenhouse gases can have serious health and environmental consequences[1,2] and therefore can impact CTB Goal E.

Data Sources:

- Long-term VMT forecasts: Federal Highway Administration[3]
- VMT in Virginia in 2019 by functional system: Federal Highway Administration[4]
- VMT in Virginia in 2019 by vehicle type: VDOT[5]
- Forecasted shares of vehicles in 2045 by energy source: Section 3.1.3, VTrans Macrotrend # 3: Adoption of Electric Vehicles
- Impact on CO2e emissions due to electrification of transportation: Section 3.1.3, VTrans Macrotrend # 3: Adoption of Electric Vehicles
- Real-world fuel economy: EPA[6]

[1] U.S. Environmental Protection Agency (2020). Smog, Soot, and Other Air Pollution from Transportation. Last updated November 20, 2020. Accessed June 10, 2021.

[2] U.S. Environmental Protection Agency (2020). Greenhouse Gases. Last updated March 19, 2020. Accessed June 10, 2021.

[3] Federal Highway Administration (2020). FHWA Forecasts of Vehicle Miles Traveled (VMT): Spring 2020.

[4] Federal Highway Administration (2020). "Functional System Travel – 2019 Annual Vehicle-Miles." Highway Statistics 2019.

[5] Virginia Department of Transportation (2019). Daily Vehicle Miles Traveled (DVMT) by FHWA Vehicle Class. VDOT Report ID – VMT 2020.

[6] U.S. Environmental Protection Agency (2019). "Table 2.1. Production, Estimated Real-World CO2, and Fuel Economy for Model Year 1975–2019." 2019 EPA Automotive Trends Report.

- Emissions tonnage by vehicle weight class: EPA[1]
- Change in emissions due to electrification: Energy Innovations[2]
- Change in truck VMT due to e-commerce: Section 3.1.5., VTrans Macrotrend #5: Growth in E-commerce
- Change in truck VMT due to automation: Section 3.1.6., VTrans Macrotrend #6: Greater Automation of Goods and Services

Calculations:

These calculations rely on research conducted for Step 1. As indicated in Table 11, the following six (6) macrotrends are expected to influence Tailpipe Emissions. The impact of each is calculated using order of influence (Table 12). The Macrotrends' impact on tailpipe emissions is estimated under the relevant headers before being combined to derive a cumulative range of estimates for tailpipe emissions.

- Macrotrend # 2: Adoption of Highly Autonomous Vehicles
- Macrotrend # 3: Adoption of Electric Vehicles
- Macrotrend # 4: Growth in Shared Mobility
- Macrotrend # 5: Growth in E-commerce
- Macrotrend # 6: Greater Automation of Automation and Services
- Macrotrend # 8: Increase in Workplace Flexibility

The combined impacts of Macrotrend # 2: Adoption of Highly Autonomous Vehicles (AV), Macrotrend # 3: Adoption of Electric Vehicles, Macrotrend # 4: Growth in Shared Mobility (Ridesourcing only) on Tailpipe Emissions is calculated using the following steps:

1. Utilize light vehicles VMT increase estimates calculated in calculation step # 7 from Section 3.3.1.

Impact of Macrotrend # 4: Growth in Shared Mobility is calculated using the following steps:

2. Utilize calculation step output to obtain the reduction in VMT due to switching light vehicle trips to micromobility. The following equation is used for each scenario to account for the change in the light vehicle VMT due to shared mobility.
   $\Delta light\ vehicles = \Delta VMT\ from\ Shared\ Mobility \times 2019\ DVMT\ all\ classes / 2019\ DVMT\ light$

   Where:

   - *ΔVMT from Shared Mobility* is the percentage change in all VMT due to growth in shared mobility. This accounts for micromobility only since ridesourcing is not expected to reduce the number of automobile miles. Micromobiilty is assumed to be emissions-free.
   - 2019 *DVMT all classes* is the daily VMT in 2019 from all vehicle classes in Virginia. This is used to scale the change in VMT to make it account for light vehicles only.[3]
   - 2019 *DVMT light* is the daily VMT in 2019 from motorcycles, passenger cars, and two-axle 4-tire single unit vehicles.[4]

Impact of Macrotrend # 5: Growth in E-Commerce on Tailpipe Emissions is calculated using the following steps:

3. Utilize calculation step # 13 output from Section 3.3.1 to estimate light vehicle VMT avoided due to e-commerce,
4. Utilize calculation step # 14 output from Section 3.3.1 to estimate the increase in medium and heavy trucks VMT in the future year 2045 due to growth in e-commerce.

[1] U.S. Environmental Protection Agency (2017). National Emissions Inventory Data - Virginia.

[2] Energy Innovations (n.d.). Virginia Energy Policy Simulator (EPS) Summary Documentation.

[3] Virginia Department of Transportation (2019). Daily Vehicle Miles Traveled (DVMT) by FHWA Vehicle Class. Series 220 – DVMT by Federal Vehicle Class. Last updated May 13, 2020.

[4] Virginia Department of Transportation (2019). Daily Vehicle Miles Traveled (DVMT) by FHWA Vehicle Class. Series 220 – DVMT by Federal Vehicle Class. Last updated May 13, 2020.

Impact of Macrotrend # 6: Greater Automation of Production and Services on Tailpipe Emissions is calculated using the following steps:

5. Utilize calculation step # 15 output from Section 3.3.1to calculate the change in medium and heavy vehicles VMT due to greater production automation and 3D printing.

Impact of Macrotrend # 8: Increase in Workplace Flexibility on Tailpipe Emissions is calculated using the following steps:

6. Utilize estimated reduction in light vehicles VMT due to VTrans Macrotrend # 8: Increase in Workplace Flexibility calculated in calculation step # 22 from section 3.3.1

Estimate the cumulative impacts of the previous Macrotrends:

7. Combine the independent effects of each macrotrends' effect on that vehicle class's VMT using the following equation for the "low," "medium," and "high" scenarios for different vehicle weight classes.
   $\text{combined effect} = \prod_{m \in M} (1 + \text{effect on } VMT_m)$

   Where:
   - m is a Macrotrend out of all applicable macrotrends M.
   - $\text{effect on } VMT_m$ is the percentage change in that vehicle class's VMT that is expected due to macrotrend m.
   - $\prod_{m \in M}$ refers to the product operator, meaning that it multiplies the sequence of Macrotrends m out of all relevant Macrotrends M.

Table 27: Cumulative Net Impact of Macrotrends on VMT Relevant for Tailpipe Emissions by Vehicle Weight Class

Macrotrend #	Light-duty Vehicle			Medium-duty Vehicle			Heavy-duty Vehicle		
	Low Impact	Medium Impact	High Impact	Low Impact	Medium Impact	High Impact	Low Impact	Medium Impact	High Impact
Adoption of Highly Autonomous Vehicles Adoption of Electric Vehicles	5.6%	10.5%	21.7%						
Growth in Shared Mobility	0.0%	-0.1%	-0.2%						
Growth in E-commerce	-0.1%	-0.3%	-0.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Greater Automation of Automation and Services				0.0%	0.1%	0.2%	-0.7%	-5.7%	-10.2%
Increase in Workplace Flexibility	-1.3%	-2.3%	-3.2%						
Net Impact of Macrotrends	4.0%	7.6%	17.1%	0%	0.1%	0.2%	-0.7%	-5.7%	-10.2%

[1] Assumption: Annual emissions tonnage is not available therefore an average of heavy-duty and light-duty vehicles emission tonnage is utilized.

8. Calculate tons per mile by converting annual emission tonnage to daily emission tonnage and dividing by daily VMT called "Per VMT" in Table 28.

Table 28: Emissions by Vehicle Weight Class

Vehicle type	Emission tonnage		
	Annual	Daily	Per VMT
Heavy-duty Vehicles	9,123,663	24,996	0.002355
Medium-duty Vehicles[1]	Not available	Not available	0.001412
Light-duty Vehicles	37,366,768	102,375	0.000468

9. Calculate internal combustion engine (ICE) emissions reduction estimated reduction in tailpipe emissions due to improvements ICE vehicles' fuel efficiency or between 2017 (which is the year for which emissions tons per mile were calculated) and 2045. Data for fuel efficiency is from the Environmental Protection Agency's (EPA) real-world fuel economy between 1990 and 2019 and extrapolated to 2045 using linear trends. The resulting decrease in fuel consumption (called "ICE emissions reduction") is 13.4%.

10. Estimate base year (2019) tailpipe emissions[2] in tons per mile[3] utilizing annual emission tonnage by vehicle weight class.[4]

    $Baseline\ emissions = \sum_{v\ V} VMT_v \times tons\ per\ mile_v \times ICE\ emissions\ reduction$

    Where:

    - VMT_v is annual VMT for vehicle class *v*
    - *v* is a vehicle class out of all vehicle weight classes *V*
    - *tons per mile*$_v$ is the emissions of vehicle class v in tons shown in calculation step # 7.
    - *ICE emissions reduction* from calculation step # 9

11. Calculate *EV effect* which is the percent of emissions that are expected to be reduced due to VTrans Macrotrend # 3: Adoption of Electric Vehicles (more details regarding this Macrotrend in calculation step # 2 of Section 3.1.3).

12. Calculate *EV share* which is the percentage of vehicles of each vehicle type that are expected to be electric in 2045 in each scenario based on Section 3.1.3, output of calculation step # 1.

13. Estimate the expected emission tonnage of each vehicle type in the low, medium, and high scenarios by multiplying their combined effect by 2019 VMT for that vehicle type, the vehicle type's emissions per mile, and the expected reduction in tailpipe emissions due to adoption of electric vehicles (formula below).

    $Expected\ emissions\ tonnage = combined\ effect \times tons\ per\ mile \times VMT \times (EV\ share \times (1 - EV\ effect) + (1 - EV\ share) \times (1 - ICE\ emissions\ reduction))$

[1] U.S. Environmental Protection Agency (2019). "Table 2.1. Production, Estimated Real-World CO2, and Fuel Economy for Model Year 1975–2019." 2019 EPA Automotive Trends Report.

[2] Note: The following emissions types are included: Criteria and/or Hazardous Air Pollutant: NH3, CO, NOX, PM2.5 and PM10, SO2, VOC, Lead Greenhouse Gas (CO2, CH4, N2O, SF6)

[3] Assumption: VMT shares of light, medium, and heavy vehicles will remain roughly constant through 2045.

[4] U.S. Environmental Protection Agency (2017). *National Emissions Inventory Data - Virginia.*

Where:

- *combined effect* was calculated for each scenario and vehicle type from Table 28 after calculation step # 6.
- *tons per mile* was calculated for each light-, medium-, and heavy-duty vehicles, from calculation step # 7.
- *VMT* was calculated for each vehicle type based on the 2019 VMT by federal vehicle class from VDOT for all Virginia roads.[1]
- *EV effect* (refer to calculation step # 10)
- *EV share* (refer to calculation step # 11)
- ICE emissions reduction is the estimated reduction in ICE vehicles' tailpipe emissions due to improvements in ICE vehicles' fuel efficiency, as calculated in calculation step # 8)

14. Calculate Emissions (%) for each scenario (low, medium, high), which is the net change in tailpipe emissions due to VTrans Macrotrends (Step 1) using the following formula.
    Emissions (%) = 1 – Expected emissions/Baseline Emissions

Where:

- *Baseline emissions are the emissions without the effects of any Macrotrends.*
- *Expected emissions for each scenario are from calculation step # 12.*

Step 3: Impact of VTrans Macrotrends on CTB Goal E

The results of calculation step # 15 for the statewide analysis are included in Table 29 and should be interpreted as follows:

- Low-impact Scenario: Tailpipe emissions are estimated to decrease by 3% (equivalent to 1 – 0.97) over the 2045 no-build scenario (absence of VTrans Macrotrends (Step 1))
- Medium-impact Scenario: Tailpipe emissions are estimated to decrease by 17% (equivalent to 1 – 0.83) over the 2045 no-build scenario (absence of VTrans Macrotrends (Step 1))
- High-impact scenario: Tailpipe emissions are estimated to decrease by 69% (equivalent to 1 – 0.31) over the 2045 no-build scenario (absence of VTrans Macrotrends (Step 1))

Table 29: Estimated Impact of VTrans Macrotrends on CTB Goal E in Year 2045

CTB Goal	Surrogate for CTB Goal	Low Estimate	Medium Estimate	High Estimate
Goal E: Healthy Communities and Sustainable Transportation Communities	Tailpipe Emissions Index	0.97	0.83	0.31

Where 1.0 is 2045 business-as-usual scenario where VTrans Macrotrends have no impact.

[1] Virginia Department of Transportation (2019). Daily Vehicle Miles Traveled (DVMT) by FHWA Vehicle Class. Series 220 – DVMT by Federal Vehicle Class. Last updated May 13, 2020.

3.4. Step 4: Develop VTrans Long-term Risk & Opportunity Register

Step 4 is utilized to develop the VTrans Long-term Risk & Opportunity Register to allow for systematic and methodical identification of risks[1] and opportunities.[2] The Register documents and highlights areas requiring attention from the Commonwealth and helps organize and communicate the identified risks and opportunities across different agencies and departments to ensure a common direction and strategy to meeting the CTB Goals.

The register takes into account the work completed in Steps 1 through 3, including the order of influence established for the ten macrotrends and the magnitude of impact established in Step 3. Additionally, discussions with OIPI, VDOT and DRPT leadership, and direction from the CTB, guide the creation of the register using the following attributes:

- Description of risk or opportunity
- Probability: Estimated probability of occurrence categorized as Very High, High, Medium, and Low
- Impact: Estimated impact on CTB Goals and Objectives in the event of occurrence categorized as Very High, High, Medium, and Low
- Proximity: Temporal dimension to reflecting categorized as Near-term, Mid-term, and Long-term
- Priority: Assigned relative priority for the commonwealth accounting for probability, impact and proximity categorized as Very High, High, Medium, and Low.

[1] The term risk is defined as a situation or scenario wherein there is some uncertainty and at least some probability of a negative outcome or result.

[2] The term opportunity is defined as a situation or scenario wherein there is some uncertainty and at least some probability of a positive outcome or result.

3.5. Step 5: Track Macrotrends

Step 5 identifies trackers that OIPI shall utilize to provide annual updates to the CTB on the VTrans Macrotrends identified in Step 1, as well as any changes to the items identified in the VTrans Risk & Opportunity Register. Updates shall take place once per calendar year, in July or September.

Table 30: VTrans Trend Trackers

Macro-trend #	Macrotrend Title	VTrans Trend Trackers	Expected Data Source
1	Increase in Flooding Risk	▪ Number of directional miles at-risk from sea-level rise ▪ Number of directional miles at-risk from storm surge ▪ Number of directional miles at-risk from inland/riverine flooding	Appendix 1
2	Adoption of Highly Autonomous Vehicles	▪ Market Penetration of Semi-Autonomous (Levels 1 and 2) Vehicles ▪ Attitude and Preferences for Adoption of Semi-Autonomous (Levels 1 and 2) Vehicles ▪ Market Penetration of Highly Autonomous (Levels 3 and 4) Vehicles ▪ Attitude and Preferences for Adoption of Highly Autonomous (Levels 3 and 4) Vehicles	VTrans State of Transportation Biennial Survey
3	Adoption of Electric Vehicles	▪ Number of Electric Vehicles ▪ Market Penetration of Electric Vehicles ▪ Attitude and Preferences for Adoption of Electric Vehicles	Virginia Department of Motor Vehicles VTrans State of Transportation Biennial Survey
4	Growth in Shared Mobility	▪ Access to Shared Mobility Services ▪ Utilization of Shared Mobility Services by Type	VTrans State of Transportation Biennial Survey
5	Growth in E-commerce	▪ Number of Warehouse and Distribution Centers ▪ Square Footage of Warehouse and Distribution Centers ▪ Share of E-commerce Sales (Business-to-business, business-to-customers) ▪ Number of Jobs in Goods Movement Dependent Industries	Transearch US Census Quarterly E-Commerce Report US Census Annual Report for Wholesale Trade US Bureau of Labor Statistics State Occupational Employment and Wage Estimates for Virginia
6	Greater Automation of Production and Services	▪ Value output of 3D Printing ▪ Number of short-range drone deliveries ▪ Number of long-range drone deliveries	Deloitte 3D Printing Market estimates

Macro-trend #	Macrotrend Title	VTrans Trend Trackers	Expected Data Source
7	Increase in Workplace Flexibility	▪ Number of Workers with Workplace Flexibility ▪ Utilization of Workplace Flexibility	VTrans State of Transportation Biennial Survey Bureau of Labor Statistics, Current Population Survey
8	Growth of Professional Service Industry	▪ Share of Professional Service Industry ▪ Number of STEM Jobs	IHS Markit, Woods & Poole, Employment Estimates by NAICS 2-digit code
9	Growth of the Age 65+ Cohort	▪ Number of Virginians with Age 65 or higher ▪ Share of Age 65+ Cohort	US Census Decennial reports and American Community Survey, Population by Age
10	Population and Employment Shift	▪ VTrans Land Use Vitality (LUV) Index ▪ Population ▪ Employment ▪ Income	Weldon Cooper Center for Public Service, Annual Population Estimates Bureau of Labor Statistics Quarterly Census of Employment and Wages Woods & Poole, Moody's Analytics, Income Estimates

APPENDIX 1: VTRANS MACROTREND # 1: INCREASE IN FLOODING RISK

1: SCOPE OF THE VTRANS VULNERABILITY ASSESSMENT

This is a screening-level assessment of the vulnerability of Virginia's transportation system, more specifically all public roadways and VDOT-maintained structures (bridges and culverts) covered in the National Bridge Inventory (NBI), to projected sea level rise, storm surge, and inland/riverine flooding scenarios. The focus is on identifying and conveying the relative magnitude of risks to the transportation system to: (1) increase awareness; (2) identify strategic actions to increase readiness; (3) identify areas for data and research to improve accuracy and reliability of forecasted vulnerabilities.

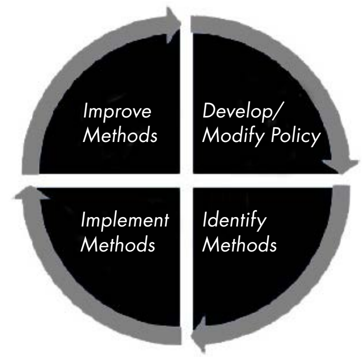
The VTrans Vulnerability Assessment is not intended to be used to develop location-specific recommendations for the following reasons:

- While this screening-level assessment narrows the universe of transportation infrastructure for further review, it does not replace the need for the collection of more precise location-specific data.
- The transportation system is one of the many infrastructure components impacted by the forecasted vulnerabilities. Therefore, it would be advisable to conduct a more comprehensive area-wide assessment for all components of physical and social infrastructure as some vulnerability mitigation strategies might require systematic solutions such as perimeter protection.

This assessment can form the basis for a few VTrans Strategic Actions (Figure 1) focusing changes to existing policies and processes for transportation infrastructure maintenance and development to allow for systematic risk mitigation.

1.1 Opportunities for Continuous Improvement

Figure 2: Opportunities for Continuous Improvement



The execution of the methodology outlined in this technical memorandum relies on data and computations to ensure transparent, data-driven, and replicable methods. The following should be noted:

- **Data:** The execution relies on data from state and national sources. Each of these sources relies on various methods, techniques, and technologies to develop its datasets and, therefore, has its own limitations such as:
  - Lack of readily usable data: There are instances in which the current completeness and accuracy of datasets makes it unsuitable used to execute the methodology outlined in this technical memorandum. For example, more information on roadway horizontal and vertical geometry will significantly improve quality and accuracy of the vulnerability assessment results. Similarly, availability of alternative routes will help provide more relevant data to determine the Adaptive Capacity of a facility (more details in Section 2) and thereby improve accuracy of the VTrans Vulnerability Assessment. Therefore, application of transportation planning or engineering judgment is recommended prior to developing solutions.
  - Scope of the task: The availability of data largely governed the scope of the task. For example, more precise information on transit and rail assets can help make the VTrans Vulnerability Assessment more multimodal in nature.
- **Computations:** The sheer size and magnitude of the effort relies on complex computations to perform an analysis on more than one million roadway segments. The effort requires synthesis, format conversions, and computations, such as in the following examples, that could result in inadvertent errors.
  - Units: Different data sources have different units. Some datasets are available by directional segment, whereas other datasets are available at the area or sub-area level.
  - Levels of aggregations: Some datasets are more aggregated than others. For example, historical weather data are available as point data and were aggregated and assigned to roadway segments (See Appendix 1-F).
  - Frequency of data collection: Some datasets are collected in real time, whereas other datasets are updated once per year or even less frequently.

- Frequency of data reporting: In addition to the variations in data collection schedule, some datasets are reported in real time, where other datasets are reported once a year.
- Data formats: Transportation assets are currently available in vector formats primarily as line or points features where weather related datasets are primarily in raster formats. One of the significant limitations of vector formats is that they are not ideal for data on continuous scales such as those available for weather, precipitation, etc. This limitation results in less accuracy (refer to Appendix 1-E) and should be a higher priority for any future work.

The Statewide Transportation Planning Team at OIPI sees these considerations as opportunities for continuous improvement. Methods and techniques outlined in this memorandum can continue to evolve and improve based on advances in technology, data quality, data collection, and reporting tools.

2: DEFINITIONS

A first step in conducting the VTrans Vulnerability Assessment is to establish foundational definitions of the terms vulnerability and resilience.

2.1.1 Definition of Vulnerability

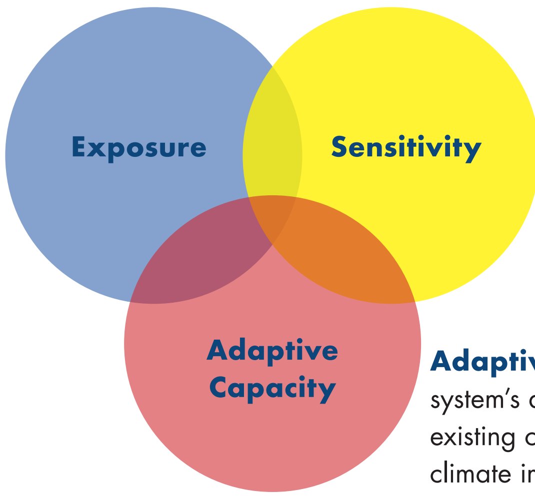
The VTrans Vulnerability Assessment is based on the following definition of vulnerability: vulnerability is a function of exposure to a hazard(s), the sensitivity to the given hazard, and adaptive capacity or the system's ability to cope.

A system can be vulnerable to many natural and man-made hazards. This assessment's focus is specifically vulnerability to flooding due to sea level rise, storm surge, and inland/riverine flooding.

This definition is based on the Federal Highway Administration (FHWA)[2] definition that breaks down vulnerability as a function of an asset or system's exposure, sensitivity, and adaptive capacity (Figure 3).

Figure 3: Components of Vulnerability

Exposure: whether the asset or system is located in an area experiencing direct effects of climate variables.



Sensitivity: how the asset or system fares when exposed to a climate variable.

Adaptive capacity: the asset or system's ability to adjust to or cope with existing climate variability or future climate impacts.

- **Exposure:** whether the asset or system is located in an area experiencing direct effects of climate variables. For example, a road that could experience flooding and inundation due to its location in a low-lying area. The nature and degree to which an asset is exposed to significant climate variations (i.e., asset location relative to a stressor).
- **Sensitivity:** how the asset or system fares when exposed to a climate variable. For example, a tunnel could be more sensitive to flooding due to challenges removing water. (i.e., if all assets were equally exposed, which assets would experience the greatest damage?).
- **Adaptive capacity:** the asset or system's ability to adjust to or cope with existing climate variability or future climate impacts. For example, redundant or alternative routes that could be used to reach the same location would increase adaptive capacity compared to a route that is the only source of access. The ability of a system or asset to adjust to the impacts of climate change to moderate potential damages, to take advantage of opportunities, or to cope with consequences.

2.1.2 Definition of Resilience

The VTrans Vulnerability Assessment is based on the following definition of resilience or resiliency: the capability to anticipate, prepare for, respond to and recover from extreme weather event(s) with minimum damage to social well-being, infrastructure, the economy, and the environment.

[2] Federal Highway Administration, Vulnerability Assessment and Adaptation Framework 3rd Edition

3: VULNERABILITY SCENARIOS AND METHODOLOGY

3.1 Scenarios

Several factors influence the extent and frequency of exposure to sea level rise, storm surge, and inland/riverine flooding. Three scenarios were developed to account for the following uncertainties in the projections and to provide a range of vulnerability.

- Policy uncertainty: globally, countries are making commitments that may potentially reduce frequency and intensity of extreme natural events. However, there are uncertainties around timeframes for implementation and adherence to the commitments.
- Scientific uncertainty: Available literature indicates that the understanding of complex natural systems that govern climate is evolving. This imperfect understanding introduces another source of uncertainty.
- Model uncertainty: Even with a good understanding of scientific processes, it is difficult to represent them.

This Vulnerability Assessment applied the three (3) scenarios to each of the three (3) hazards, resulting in a total of nine (9) Vulnerability Scores.

Appendix 1 Table 1: Hazard Types and Data Sources

Hazard	Data Source of Projected Hazard	Scenario 1	Scenario 2	Scenario 3
Sea Level Rise	Virginia Institute of Marine Sciences (VIMS)	Intermediate sea level rise scenario (Year 2040)	Intermediate-High sea level rise scenario (Year 2040)	Extreme sea level rise scenario (Year 2040)
Storm Surge	National Hurricane Center (NHC)	Category 2 hurricane storm surge	Category 3 hurricane storm surge	Category 4 hurricane storm surge
Inland/Riverine Flooding	Federal Emergency Management Agency (FEMA) VDOT	100-year flood zone AND Historical Weather-Related Damages or Closures	500-yr flood zone AND Historical Weather-Related Damages or Closures	FEMA 500-yr flood zone with varying width buffer (10-200ft) based on floodplain width AND Historical Weather-Related Damages or Closures (Appendix 1-F)

3.1.1 Data sources for Scenarios

- **Sea level rise:** The sea level rise scenarios are based on National Oceanic and Atmospheric Administration's (NOAA) 2017 report, Global and Regional Sea Level Rise Scenarios for the United States and one of the scenarios is consistent with Governor Northam's Executive Order Number 24 *(2018): Increasing Virginia's Resilience to Sea Level Rise*. The Virginia Flood Risk Management Standard (VFRMS) (Executive Order 45) satisfies the directive in Executive Order 24 by setting standards for State-owned buildings in coastal and inland flood prone areas based on the NOAA Intermediate-High scenario curve.

  The sea level rise scenarios utilized Sewells Point tide gauge to determine Relative Sea Level Change (RSLC). With a baseline year 2000, these RSLC values were added to today's mean high water (MHW) level to determine future MHW levels. These datasets were obtained from the Center for Coastal Resources Management at VIMS and include both the extent and depth of flooding. The 2017 NOAA report (Appendix 1-D) provides six emission-based scenarios aligned with conditional probability storylines and global model projections, of which the following three were applied in the VTrans Vulnerability Assessment:

  - Intermediate, Relative Sea Level Change (RSLC) of 1.38 feet
  - Intermediate-High, RSLC of 1.78 feet
  - Extreme, RSLC of 2.46 feet

[3] Anthropocene Sea Level Change: A History of Recent Trends Observed in the U.S. East, Gulf, and West Coast Regions

- **Storm surge:** The storm surge scenarios are based on NHC hydrodynamic Sea, Lake and Overland Surges from Hurricanes (SLOSH) model which simulates storm surge from tropical cyclones based on present day sea levels. The SLOSH model uses a representative sample of hypothetical storms (up to 100,000) using varying intensity, forward speed, radius of maximum wind, storm direction, and tide level. Each storm combination is simulated at 5 to 10-mile increments along the coast. For each storm intensity (Category 1-5), the maximum storm surge height among all simulations is catalogued at each grid point in the model. The resulting Storm Surge Hazard Maps represent the worst-case flooding scenario during high-tide for each storm category.
- **Inland/riverine flooding:** The inland/riverine flooding flooding scenarios are based on a combination of FEMA Flood Zones derived from the Flood Insurance Rate Map (FIRM) via FEMA's National Flood Hazard Layer database, and observed historical weather events from Virginia's 511 system.[1] The scenarios also rely on historical flooding documented by VDOT.

3.2 Methodology

Key attributes of the VTrans Vulnerability Assessment methodology are outlined below:

- **Methodology Source:** The VTrans Vulnerability Assessment is based on the FHWA Vulnerability Assessment Scoring Tool (VAST) for each of the three scenarios outlined in Section 3.1. This approach uses data on asset location and other key attributes as indicators of each of the three components of vulnerability: (1) Exposure; (2) Sensitivity; and, (3) Adaptive Capacity.
- **Approach:** the VTrans Vulnerability Assessment uses a point-based system to determine an asset's level of vulnerability. Similar to FHWA's VAST tool, the VTrans Vulnerability Assessment relies on an indicator-based approach. Indicators are representative elements such as location, existing flood protection, and projected climate stressors that can be used as proxy measurements for the exposure, sensitivity, or adaptive capacity of a specific asset. Indicators within each of the three main component categories (Exposure, Sensitivity, and Adaptive Capacity) were weighted within their respective category. Then each of the three main components are also given a weighting.

  Consistent with the scope outlined in Section 1, two sets of indicators were developed - one for roadways and one for structures because: (a) structures, as an asset type, have different characteristics and therefore different sensitivity; and, (2) generally, more precise and complete datasets are available for structures. Tables 2 and 3 list component and indicator weights for roadway segments and structures, respectively. If an asset is exposed to inundation, a three-point score is developed for each indicator which is then weighted and summed per the weighting in Tables 2 and 3 to calculate a vulnerability score for each asset by hazard type.

Appendix 1 Table 2: Component and Indicator Weightings for Roadway Segments

Component	Component Weight	Indicator	Indicator Weight by Hazard Type		
			Sea Level Rise	Storm Surge	Inland/Riverine Flooding
Exposure	40%	Inundation from Sea Level Rise OR Storm Surge OR Inland/Riverine Flooding	100.0%	100.0%	100.0%
Sensitivity[2]	20%	Pavement Condition	5.0%	5.0%	5.0%
		Pavement Type	10.0%	10.0%	10.0%
		Historical Weather-Related Damages or Closures	85.0%	85.0%	85.0%
Adaptive Capacity[2]	40%	Functional Class	10.0%	10.0%	10.0%
		Hurricane Evacuation Route	15.0%	50.0%	0.0%
		Annual Average Daily Traffic (AADT)	20.0%	20.0%	20.0%
		Corridors of Statewide Significance (CoSS)	55.0%	20.0%	70.0%
Vulnerability Score	100%				

[1] See Appendix 1-F.

[2] Scores for Sensitivity, Adaptive Capacity, and Vulnerability are only developed if Exposure component indicates risk of inundation.

Appendix 1 Table 3: Component and Indicator Weightings for Structures

Component	Component Weight	Indicator	Indicator Weight by Hazard Type		
			Sea Level Rise	Storm Surge	Inland/Riverine Flooding
Exposure	40%	If Exposure to Sea Level Rise	100.0%	100.0%	100.0%
Sensitivity[1]	20%	*If Bridge:*			
		–Deck Rating	2.5%	2.5%	2.5%
		–Superstructure Rating	2.5%	2.5%	2.5%
		–Substructure Rating	5.0%	5.0%	5.0%
		If Culvert:			
		–Culvert Rating	10.0%	10.0%	10.0%
		Scour Criticality	20.0%	20.0%	35.0%
		Channel and Channel Protection	0.0%	10.0%	15.0%
		Waterway Adequacy	50.0%	40.0%	20.0%
		Historical Weather-Related Damages or Closures	20.0%	20.0%	20.0%
Adaptive Capacity[1]	40%	Hurricane Evacuation Route	15.0%	50.0%	0.0%
		Navigable Waterway	25.0%	10.0%	0.0%
		Importance Factor	60.0%	40.0%	100.0%
Vulnerability Score[1]	100%				

The following subsections describe the methods for assigning scores to each indicator on a three-point scale.

3.2.1 Exposure

The first component of the Vulnerability Assessment is an exposure analysis using a three-point scale that relies on the projected severity of impact (Table 4). For all roads and structures, a separate geospatial analysis for each hazard type is conducted. If an asset is determined to not be exposed, then the asset is not considered vulnerable and scores for sensitivity and adaptive capacity are not developed.

Appendix 1 Table 4: Exposure Criteria

Indicator	Value	Score
Inundation from Sea Level Rise[2] Locations with greater projected depths of inundation are likely to be impacted by projected changes in climate sooner, including permanent inundation.	Worst one-third of the impacted directional mileage	3
	Middle one-third of the impacted directional mileage	2
	Bottom one-third of the impacted directional mileage	1
	Not inundated	N/A
Inundation from Storm Surge event[3] Locations with greater depths of estimated inundation during hurricanes are more likely to experience frequent inundation and be greatly affected by projected changes in climate.	Worst one-third of the impacted directional mileage	3
	Middle one-third of the impacted directional mileage	2
	Bottom one-third of the impacted directional mileage	1
	Not inundated	N/A
Location Relative to FEMA Flood Zone[4] AND Historical weather-related damages or closures[5] Assets located in a floodplain and that have experienced flooding in the past are more exposed than other assets.	In flood zone AND Exposed to Historical Flood Event	3
	Outside of flood zone AND/OR not exposed to historical flood event	N/A

[1] Scores for Sensitivity, Adaptive Capacity, and Vulnerability are only developed if Exposure component indicates risk of inundation.

[2] The Center for Coastal Resources Management at the Virginia Institute of Marine Science (VIMS). This dataset includes both the extent and depth of flooding.

[3] NHC SLOSH model which simulates storm surge from tropical cyclones based on present day sea levels. This dataset includes both the extent and depth of flooding.

[4] Federal Emergency Management Agency floodplain.

[5] VDOT Operations Division. Field Name: Weather events ("WX") in VATraffic (Virginia 511). Values indicate those in the dataset accessed on December 31, 2020 for Years 2015-2020. See Appendix 1-F.

3.2.2 Sensitivity

The second component of the Vulnerability Assessment is a sensitivity analysis using a three-point scale that identifies the degree to which an exposed asset would be impacted by the exposure (i.e., if all assets were equally exposed, which assets would experience the greatest damage?). A separate weighting framework is applied to roadways and to structures, however the indicator values were applied consistently across exposure types. Table 5 and 6 summarizes the indicators, data sources, and scoring applied for both roadways and structures.

Appendix 1 Table 5: Sensitivity Criteria for Roadways

Indicator	Value	Score
Pavement Condition[1] Assets in poor condition are more likely to be damaged when exposed to flooding events.	Very Poor / Poor	3
	Fair	2
	Good / Excellent	1
Pavement Type[2] Reinforced pavements are less likely than non-reinforced pavements to be damaged when exposed to flooding events.	Asphalt	3
	Joint Reinforced Concrete Pavement	2
	Continuously Reinforced Concrete Pavement	1
Historical weather-related damages or closures[3] Assets that have experienced flooding in the past are likely to be sensitive in the future.	4+ historical events	3
	2-3 historical events	2
	1 historical event	1
	0 historical events	0

Appendix 1 Table 6: Sensitivity Criteria for Structures

Indicator	Value	Score
Deck Rating (Bridges Only)[4] Structures in serious condition are more likely to be damaged when exposed due to the exacerbation of pre-existing weaknesses.	0 (Failed Condition) 1 (Imminent Failure Condition) 2 (Critical Condition) 3 (Serious Condition) 4 (Poor Condition)	3
	5 (Fair Condition) 6 (Satisfactory Condition)	2
	7 (Good Condition) 8 (Very Good Condition) 9 (Excellent Condition)	1
	N (Not Applicable) or data not available	0

[1] VDOT Maintenance Division. Year: 2020. Field Name: CONDITION_TEXT. Values indicated in Table 5 are based on dataset accessed on April 13, 2021. Roadways where pavement condition was not available were assigned a score of 2

[2] VDOT Maintenance Division. Year 2020. Field Name: PAVEMENT_TYPE. Accessed on April 13, 2021. Roadways where pavement type was not available were assigned a score of 3.

[3] VDOT Operations Division. Field Name: Weather events ("WX") in VaTraffic (Virginia 511). Values indicate those in the dataset accessed on December 31, 2020 for Years 2015-2020. Refer to Appendix 1-F.

[4] VDOT Structure & Bridge Division. Year 2020. Field Name: DKRATING. Values indicated in Table 6 are based on dataset accessed on accessed on December 23, 2020.

Indicator	Value	Score
Superstructure Rating (Bridges Only)[1] Structures in serious condition are more likely to be damaged when exposed due to the exacerbation of pre-existing weaknesses.	0 (Failed Condition) 1 (Imminent Failure Condition) 2 (Critical Condition) 3 (Serious Condition) 4 (Poor Condition)	3
	5 (Fair Condition) 6 (Satisfactory Condition)	2
	7 (Good Condition) 8 (Very Good Condition) 9 (Excellent Condition)	1
	N (Not Applicable) or data not available	0
Substructure Rating (Bridges Only)[2] Structures in serious condition are more likely to be damaged when exposed due to the exacerbation of pre-existing weaknesses.	0 (Failed Condition) 1 (Imminent Failure Condition) 2 (Critical Condition) 3 (Serious Condition) 4 (Poor Condition)	3
	5 (Fair Condition) 6 (Satisfactory Condition)	2
	7 (Good Condition) 8 (Very Good Condition) 9 (Excellent Condition)	1
	N (Not Applicable) or data not available	0
Culvert Rating (Culverts Only[3] Culverts with condition deficiency are more likely to be exposed due to the exacerbation of pre-existing weaknesses.	0 (Structure closed; replacement necessary) 1 (Structure closed; corrective action may put back in light service) 2 (Integral wing walls collapsed, severe settlement of roadway due to loss of fill; failure; corrective action is required to maintain traffic) 3 (Any condition described in Code 4 but which is excessive in scope)	3
	4 (Large spalls, heavy scaling, wide cracks, considerable efflorescence, or opened construction joint; considerable settlement; considerable scouring or erosion; significant distortion) 5 (Moderate to major deterioration; noticeable scouring or erosion; significant distortion)	2
	6 (Deterioration; local minor scouring) 7 (Insignificant damage not requiring corrective action; minor scouring) 8 (No noteworthy deficiencies; insignificant scrape marks) 9 (No deficiencies)	1
	N (Not applicable; use if structure is not a culvert) or data not available	0

[1] VDOT Structure & Bridge Division. Year 2020. Field Name: SUPRATING. Values indicated in Table 6 are based on dataset accessed on accessed on December 23, 2020.

[2] VDOT Structure & Bridge Division. Field Name: SUBRATING. Values indicated in Table 6 are based on dataset accessed on October 1, 2020.

[3] VDOT Structure & Bridge Division. Field Name: CULVRATING. Values indicated in Table 6 are based on dataset accessed on October 1, 2020.

Indicator	Value	Score
Scour Criticality[1] Scoured assets are more likely to experience impacts when exposed.	0: Scour critical. Structure has failed and is closed to traffic. 1: Scour critical; failure of piers/abutments is imminent 2: Scour critical; extensive scour has occurred at structure foundations 3: Scour critical; foundations determined to be unstable for calculated scour conditions.	3
	4: Foundations determined to be stable for calculated scour conditions; action required to protect exposed foundations from effects of additional erosion and corrosion 5: Foundations determined to be stable for calculated scour conditions; scour within limits of footing or piles.	2
	7: Countermeasures have been installed to correct a previously existing problem with scour. Structure is no longer scour critical. 8: Foundations determined to be stable for scour conditions; calculated scour is above top of footing 9: Foundations well above flood water elevations T: Over "tidal" waters that has not been evaluated for scour but considered low risk. N: Structure not over waterway	1
	6: Scour calculation/evaluation has not been made U: Unknown or data is not available.	0
Channel and Channel Protection[2] Structures over channels with deterioration or damage are likely to be sensitive due to exacerbation of pre-existing weaknesses.	0 (Structure closed because of channel failure; replacement necessary) 1 (Structure closed because of channel failure; corrective action may put back in light service) 2 (Structure is near a state of collapse) 3 (Bank protection has failed; river control devices have been destroyed; streambed aggravation, degradation or lateral movement threaten structure and/or approach)	3
	4 (Bank and embankment protection is severely undermined; river control devices have severe damage; large deposits of debris are in the waterway) 5 (Bank protection is being eroded; river control devices and/or embankment have major damage; trees and brush restrict the channel) 6 (Bank is beginning to slump; river control devices and embankment protection have widespread minor damage; minor streambed movement evident; debris restricting waterway)	2
	7 (Bank protection is in need for minor repairs; river control devices and embankment protection have a little minor damage; banks and/or channel have minor amounts of drift) 8 (Banks are protected or well vegetated; river control devices such as spur dikes and embankment protection are not required or are in stable condition) 9 (No noticeable or noteworthy deficiencies)	1
	N (Not applicable; use only when the structure is not over a waterway) or data is not available.	0
Waterway Adequacy[3] Structures that frequently overtop and contribute to delays are likely to be sensitive in the future.	2 (Frequent overtopping) 3 (occasional overtopping of approaches and deck; significant delays) 4 (occasional overtopping of approaches; significant delays) 5 (occasional overtopping of approaches; insignificant delays)	3
	6 (slight chance of overtopping approaches and deck) 7 (slight chance of overtopping approaches and deck) 8 (Slight chance of overtopping approaches)	2
	9 (Remote chance of overtopping) 0 (structure closed)	1
	N (Not Applicable) or data is not available.	0

[1] VDOT Structure & Bridge Division. Field Name: SCOURCRIT. Values indicated in Table 6 are based on dataset accessed on accessed on October 1, 2020.

[2] VDOT Structure & Bridge Division. Field Name: Channel_and_Channel _Protection. Values indicated in Table 6 are based on dataset accessed on October 1, 2020.

[3] VDOT Structure & Bridge Division. Field Name: WATERADEQ. Values indicated in Table 6 are based on dataset accessed on October 1, 2020.

Indicator	Value	Score
Historical weather-related damages or closures[1] Assets that have demonstrated sensitivity in the past are likely to be sensitive in the future.	Sea level rise: 1+ historical events Storm surge: 4+ historical events Inland/riverine flooding: 5+ historical events	3
	Storm surge: 2-3 historical events Inland/riverine flooding: 3-4 historical events	2
	Storm surge: 1 historical event Inland/riverine flooding: 1-2 historical events	1
	Sea level rise, storm surge, or inland/riverine flooding: 0 historical events	0

Sensitivity scores for each hazard type and each scenario were calculated for roads with exposure to that hazard type under that scenario. The sensitivity scores were then grouped into 3 categories based on directional roadway mileage as outlined in Table 7. Where sensitivity score break points did not align with the target percentages, these percentages were modified to align with the next break point.

Appendix 1 Table 7: Categorization of Sensitivity Scores

Hazard	Sensitivity Score	Sensitivity Categorization
Sea Level Rise (All Scenarios)	0.45 or greater	High
	0.40 to 0.44	Medium
	Less than 0.40	Low
Storm Surge (All Scenarios)*	0.45 or greater	High
	Not applicable	Medium
	Less than 0.45	Low
Inland/Riverine Flooding (All Scenarios)	2.95 or greater	High
	2.15 to 2.94	Medium
	Less than 2.15	Low

* Manually adjusted

The distribution of scores did not allow break points to be set at exactly 33.3% of directional roadway mileage for each categorization, so these break points are set either through automated processes or manually where indicated by asterisks (*) to best approximate the target mileage shares.

[1] VDOT Operations Division. Field Name Weather events ("WX") in VaTraffic (Virginia 511). Values indicate those in the dataset accessed on December 31, 2020 for Years 2015-2020. See Appendix 1-F.

3.2.3 Adaptive Capacity

The third component of the Vulnerability Assessment is an adaptive capacity analysis using a three-point scale that identifies the ability or inability of a system or asset to adjust to the impacts of exposure. A separate weighting framework is applied to roadways and structures; however, the indicator values are applied consistently across exposure types. Tables 8 and 9 summarize the indicators, data sources, and scoring applied for both roadways and structures.

Appendix 1 Table 8: Adaptive Capacity Criteria for Roadways

Indicator	Value	Score
Roadway Functional Class[1] The transportation system may be less able to absorb impacts to assets of higher functional classification.	Interstate, other freeways or expressways (01, 11, 12) Other principal arterial (02, 14)	3
	Major and minor collector, minor arterial (06, 07, 08, 16, 17)	2
	Local (09, 19)	1
Hurricane Evacuation Route[2] Assets that are part of evacuation routes will cause greater disruption to the system if damaged.	Yes	3
	No	0
Annual Average Daily Traffic (AADT)[3] Assets with large amounts of average daily traffic are highly significant routes that are less able to cope with changes caused by climate impacts.	16,800 or higher	3
	9,100 - 16,799	2
	9,099 or lower	1
Corridors of Statewide Significance (CoSS)[4] Assets of statewide significance to the transportation network have less redundancy and therefore lower adaptive capacity.	Yes - Primary CoSS or Connector	3
	Yes - CoSS Component (nor primary)	2
	No	1

Appendix 1 Table 9: Adaptive Capacity Criteria for Structures

Indicator	Value	Score
Hurricane Evacuation Route[5] Assets that are part of evacuation routes will cause greater disruption to the system if damaged.	Yes	3
	No	0
Navigable Waterway[6] Assets over navigable waterways are more likely to experience navigation issues under future climate conditions.	Yes	3
	No or N/A	0
Importance Factor (IF)[7] Assets with a greater Importance Factor will cause greater disruption to the system if damaged.	Top one-third of the total number of structures	3
	Middle one-third of the total number of structures	2
	Bottom one-third of the total number of structures or not available	1

[1] VDOT Transportation Planning and Mobility Division. Values indicated in Table 7 are based on dataset accessed on October 1, 2020. Roadways where functional classification was not available were assigned a score of 1.
[2] Virginia Department of Emergency Management. Field Name: Hurricane Evacuation Routes
[3] VDOT Traffic Engineering Division. 2019 Data. Roadways where AADT was not available were assigned a score of 1. Roadways where AADT was not available were assigned values as indicated in Appendix 1-G.
[4] Office of Intermodal Planning and Investment. Roadways that are not designated as CoSS were assigned a value of 1.
[5] Virginia Department of Emergency Management: Hurricane Evacuation Routes (Contraflow(Y/N))
[6] VDOT Structure & Bridge Division: Navigable Waterway (Navigable Waterway)
[7] VDOT Structure & Bridge Division: Bridge Importance Factor (IF). Structures were importance factor (IF) was not available were assigned a score of 1.

Adaptive capacity scores for each hazard type and each scenario were calculated for roads with exposure to that hazard type under that scenario. The adaptive capacity scores were then grouped into 3 categories based on directional roadway mileage as outlined in Table 10. Where adaptive capacity score break points did not align with the target percentages, these percentages were modified to align with the next break point.

Appendix 1 Table 10: Categorization of Adaptive Capacity Scores

Hazard	Adaptive Capacity Score	Adaptive Capacity Categorization
Sea Level Rise (All Scenarios)*	0.85 or greater	High
	Not applicable	Medium
	Less than 0.85	Low
Storm Surge (All Scenarios)*	0.50 or greater	High
	Not applicable	Medium
	Less than 0.50	Low
Inland/Riverine Flooding (All Scenarios)	1.10 or greater	High
	0.90 to 1.09	Medium
	Less than 0.90	Low

* Manually adjusted

Footnote to table: The distribution of scores did not allow break points to be set at exactly 33.3% of directional roadway mileage for each categorization, so these break points are set either through automated processes or manually where indicated by asterisks (*) to best approximate the target mileage shares.

Section 3.2.4 Vulnerability Assessment Score

Vulnerability scores for each hazard type and each scenario were calculated for roads with exposure to that hazard type under that scenario. The vulnerability scores were then grouped into 3 categories based on directional roadway mileage as outlined in Table 11. Where vulnerability score break points did not align with the target percentages, these percentages were modified to align with the next break point.

Appendix 1 Table 11: Categorization of Vulnerability Scores

Hazard	Vulnerability Score	Vulnerability Categorization
Sea Level Rise (Extreme)	2.00 or greater	High
	1.60 to 1.99	Medium
	Less than 1.60	Low
Sea Level Rise (Intermdiate-High and Intermediate)	2.20 or greater	High
	1.60 to 2.19	Medium
	Less than 1.60	Low
Storm Surge (All Scenarios)	1.80 or greater	High
	1.40 to 1.79	Medium
	Less than 1.40	Low
Inland/Riverine Flooding (All Scenarios)	2.80 or greater	High
	2.60 to 2.79	Medium
	Less than 2.59	Low

Footnote to table: The distribution of scores did not allow break points to be set at exactly 33.3% of directional roadway mileage for each categorization, so these break points are set to best approximate the target mileage shares.

Appendix 1-A: List of Acronyms

AADT	Annual Average Daily Traffic
CDOT	Colorado Department of Transportation
CoSS	Corridor of Statewide Significance
CTB	Commonwealth Transportation Board
DOT	Department of Transportation
DRPT	Department of Rail and Public Transportation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FIRM	Flood Insurance Rate Map
GMSL	Global Mean Sea Level
HRPDC	Hampton Roads Planning District Commission
IF	Importance Factor
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Laser Imaging Detection and Ranging (system)
MassDOT	Massachusetts Department of Transportation
MPO	Metropolitan Planning Organization
NBI	National Bridge Inventory
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
OIPI	Office of Intermodal Planning and Investment
SANDAG	San Diego Association of Governments
SLOSH	Sea, Lake and Overland Surges from Hurricanes
TMPD	Transportation Planning and Mobility Division.
USGCRP	U.S. Global Change Research Program
VAST	Vulnerability Assessment Scoring Tool
VDOT	Virginia Department of Transportation
VFRMS	Virginia Flood Risk Management Standard
VIMS	Virginia Institute of Marine Sciences

Appendix 1-B: Literature Review

1-B.1: Definition of Vulnerability

According to the Intergovernmental Panel on Climate Change (IPCC), vulnerability is "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt."[1] The U.S. Global Change Research Program (USGCRP) defines vulnerability as "the degree to which physical, biological and socio-economic systems are susceptible to and unable to cope with adverse impacts of climate change."[2]

In the context of transportation systems, vulnerability refers to the susceptibility of a system to hazards, including the physical vulnerability of users and the potential damage or change in service provision of the transportation system.[3] In the academic literature and transportation studies, the definition of vulnerability used by Berdica (2002) is referenced commonly. This definition states that the "vulnerability of a road transportation system is the susceptibility to incidents that can result in a considerable reduction in road network serviceability."[4]

FHWA provides a comprehensive definition that breaks down vulnerability as a function of an asset or system's exposure, sensitivity, and adaptive capacity. This definition reflects the current state of the practice for State Department of Transportations (DOT) and Metropolitan Planning Organizations (MPO).

- **Exposure:** whether the asset or system is located in an area experiencing direct effects of climate variables. For example, a road that could experience flooding and inundation due to its location in a low-lying area.
- **Sensitivity:** how the asset or system fares when exposed to a climate variable. For example, a tunnel could be more sensitive to flooding due to challenges removing water.
- **Adaptive capacity:** the asset or system's ability to adjust to or cope with existing climate variability or future climate impacts. For example, redundant or alternative routes that could be used to reach the same location would increase adaptive capacity compared to a route that is the only source of access. Note that this component of vulnerability is optional and often redundant with criticality. Criticality, which is independent from vulnerability, captures the importance of an asset to the transportation system or region as a whole. Criteria for evaluating an asset's criticality may include: average daily traffic, functional classification, goods movement levels, access to employment/ educational/medical facilities, degree of redundancy, and role in emergency management.

While some transportation systems have directly used the FHWA definition, others modify it. For example, the Hampton Roads Planning District Commission (HRPDC) defines vulnerability as a combination of sensitivity and adaptive capacity.[5] Under the HRPDC definition, a system or area would be considered more vulnerable if it is highly sensitive and has low adaptive capacity. Other possible definitions of vulnerability may not include adaptive capacity or may substitute criticality (i.e., identifying which assets are of the greatest importance, such as an evacuation route upon which a significant population depends) in their assessments.

1-B.2: Definition of Resilience

FHWA defines resilience or resiliency as "the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions."[6] When defining resilience, most State DOTs, MPOs, and the other transportation organizations use a similar approach to FHWA, focusing on the ability to prepare for and recover from disasters and disruptive events.

Table B-1: provides examples of how DOTs and MPOs define resilience, while Table B-2 provides examples of how agencies

[1] Intergovernmental Panel on Climate Change. Glossary. Accessed 13 January 2019.

[2] U.S. Global Change Research Program. Glossary. Accessed 13 January 2019.

[3] Cova, Thomas J., and Steven Conger. 2003. *"Transportation hazards" in Transportation Engineers' Handbook*. Ed. Myer Kutz.

[4] Berdica, Katja. 2002. An introduction to road vulnerability: what has been done, is done and should be done. Transport Policy, Elsevier, vol. 9(2), pages 117-127. =

[5] Hampton Roads Planning District Commission. 2010. Climate Change in Hampton Roads: Impacts and Stakeholder Involvement.

[6] Federal Highway Administration. December 2014. FHWA Order 5520.

have incorporated resilience into their goals and objectives. The FHWA report, [Integrating Resilience into the Transportation Planning Process: White Paper on Literature Review Findings], provides additional examples of resilience definitions and goals. The greatest differences between definitions among the DOTs and MPOs is how the agencies propose to build that ability. Some emphasize the importance of system adaptive capacity and robustness, while others prioritize swiftness in the recovery response. The tables identify the core components of the definitions and goals, including whether the statement is focused on community or transportation resilience (or both), and whether it includes advance preparation for disruptions, reaction (e.g., response and recovery) or both.

Table 1-B-1: Examples of How Agencies Define Resilience and the Core Components of the Definition

Agency	Definition	Community	Transportation	Preparation	Reaction
Alaska DOT	We will improve system resiliency of freight and passenger transportation to reduce the safety and security risks of natural events such as earthquakes, climate change, and man-made disasters (e.g., accidents)[1]		•	•	
Anchorage Metropolitan Area Transportation Solutions (Anchorage, AK)	Resilience means "how to work around outcomes to get back up running quickly"[2]		•		•
Arkansas DOT	The ability to reduce the possibility of failure, adapt and recover from a disruptive event and/or gradual external changes over time. It also implies transformation, so not only is the infrastructure service able to survive or recover but it can adapt to a changing environment in which it operates[3]		•	•	•
Baltimore Regional Transportation Board (Baltimore, MD)	Resilience means the transportation system is "better able to adapt to a variety of potentially significant future changes."		•	•	
Delaware DOT	Encompass[ing] the ability to withstand and recover from an incident in order to provide critical transportation services during the incident and through the recovery process[4]		•	•	•
Caltrans	Resilient transportation facilities: Transportation facilities that are designed and operated to reduce the likelihood of disruption or damage due to changing weather conditions.		•	•	
Colorado DOT	Resiliency incorporates extreme weather, economic adversity, emergency management, and security[5]		•		•
Hampton Roads Planning District Commission	The ability to recovery quickly with minimal lasting damage from an event[6]		•		•

[1] Alaska DOT. December 2016. Alaska Statewide Long-Range Transportation Policy Plan.

[2] Anchorage Metropolitan Area Transportation Solutions. May 2012. 2035 Metropolitan Transportation Plan.

[3] Arkansas Highway and Transportation Department. 2016. Arkansas Long Range Intermodal Transportation Plan.

[4] DelDOT. 2017. *Strategic Implementation Plan for Climate Change, Sustainability and Resilience for Transportation.*

[5] Colorado Department of Transportation. Statewide Transportation Plan.

[6] HRPDC. 2010. Climate Change in Hampton Roads: Impacts and Stakeholder Involvement.

Agency	Definition	Community	Transportation	Preparation	Reaction
Iowa DOT	Not explicitly defined, though it is contextualized in climate change and extreme weather: "resiliency has become increasingly important at all levels of planning, from designing projects to withstand extreme weather events to having plans in place for responding to emergency weather situations;" "System resiliency requires a proactive approach to extreme weather events and other large-scale incidents that threaten the continuity of system operations. The Iowa DOT seeks to minimize the impact of extreme weather by intentionally designing and managing certain routes to be resistant to extreme weather, and to move people and goods throughout the state both during and after extreme weather events.")[1]		•	•	•
Metropolitan Council (St. Paul, MN)	Resilience strategies recognize the difficulty of predicting what the impacts of climate change will be and emphasize increasing our flexibility to survive and thrive regardless of how climate change develops[2]	•		•	•
Metropolitan Planning Commission (Oakland, CA)	Enhance climate protection and adaptation efforts, strengthen open space protections, create healthy and safe communities, and protect communities against natural hazards[3]	•		•	•
Minnesota DOT	Reducing vulnerability and ensuring redundancy and reliability to meet essential travel needs[4]		•	•	•
Northeast Ohio Areawide Coordinating Agency (Cleveland, OH)	Resiliency is a process for managing complex infrastructures rather than a single outcome… As such, a resiliency framework takes an adaptive life-cycle approach to tackling the dynamic challenges that confront today's complex infrastructure systems. Embedded in it is the capability to protect its assets, anticipate and detect threats, prevent risks of known failures, withstand unanticipated disruptions, and respond and recover rapidly when the worst does happen[5]	•	•	•	•
Rockingham Planning Commission (Exeter, NH)	Capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment[6]	•	•	•	•
San Diego Association of Governments (SANDAG, San Diego, CA)	Making our region more resilient to the consequences of climate change means increasing the capacity of our communities, economy, and environment to cope with hazardous events such as storms, heat waves, wildfires, and ongoing drought[7]	•		•	•
Tennessee DOT	Resilience is the ability of the transportation system to withstand and recover from incidents[8]		•	•	•

[1] Iowa DOT. Iowa in Motion 2045.

[2] Metropolitan Council. 2040 Thrive MSP: One Vision, One Metropolitan Region.

[3] Metropolitan Planning Commission. Plan Bay Area 2040.

[4] Minnesota DOT. January 2017. Minnesota Statewide Multimodal Transportation Plan 2017 to 2036.

[5] Northeast Ohio Areawide Coordinating Agency (NOACA). June 2017. Aim Forward 2040.

[6] Rockingham Planning Commission. September 2017. 2040 LRTP Public Comment Draft.

[7] San Diego Association of Governments (SANDAG). San Diego Forward: The Regional Plan.

[8] Tennessee DOT. TDOT 25-YEAR LONG-RANGE TRANSPORTATION POLICY PLAN: Safety, Security, and Transportation Resilience Policy Paper

Agency	Definition	Community	Transportation	Preparation	Reaction
USGCRP	A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment[1]	•	•	•	•
Wisconsin DOT	A resilient transportation system is able to quickly respond to unexpected conditions and return to its usual operational state[2]		•		•

Table 1-B-2: Examples of How Agencies Incorporate Resilience into Goals and Objectives, and the Core Components of the Goals

Agency	Resilience Goals & Objectives	Community	Transportation	Preparation	Reaction
Boston MPO	The MPO has incorporated resilience into its system preservation goal by giving projects points for improving important evacuation routes, addressing flooding issues related to sea level rise, and helping to implement part of a climate adaptation plan[3]	•	•	•	•
Caltrans	Caltrans states that it encourages resilience planning to reduce the likelihood, magnitude, duration, and cost of disruptions associated with extreme weather and other effects of changing climatic conditions to the transportation system[4]		•	•	•
Colorado DOT (CDOT)	CDOT identifies resiliency as a key strategic policy action which addresses multiple goals, such as its safety, mobility, and system maintenance goals. The Strategic Action Plan states that all modes could be enhanced by improving the resiliency and redundancy of the transportation system to address the potential effects of extreme weather and economic adversity, emergency management, and security[2]	•	•	•	•
Massachusetts DOT (MassDOT)	Within their Long-Range Transportation Plan, Statewide Intelligent Transportation Systems Strategic Plan, MassDOT has several resilience-related goals and objectives: ▪ MassDOT is planning for the resilience of the system as they respond to the growing impacts of climate change through Vulnerability Assessments and the incorporation of climate and sea level considerations into planning processes and construction practices. ▪ A core function of government and transportation organizations is to ensure public safety and to secure the total system against natural and man-made catastrophes.[5]	•	•	•	•

[1] U.S. Global Change Research Program. Glossary. Accessed 13 January 2019.

[2] Wisconsin DOT. October 2009. Connections 2030.

[3] Boston Region MPO. 2015. Long-range Transportation Plan

[4] Caltrans. 2016. California Transportation Plan 2040.

[5] MassDOT. 2013. Statewide Intelligent Transportation Systems Strategic Plan.

1-B.3: Review of Virginia Transportation Vulnerability Assessments

The following studies were reviewed:

- The *Commonwealth of Virginia Hazard Mitigation Plan*, which profiles 13 hazards, including communicable disease, drought, earthquake, flooding, flooding due to impoundment failure, karst, landslide, land subsidence, non-rotational wind, solar storm, tornado, wildfire, and winter storm.[1]
- The Virginia Institute of Marine Science (VIMS), Center for Coastal Resources Management, and William & Mary *Recurrent Flooding Study for Tidewater Virginia* report, which assesses flood risk across the coastal zone of Virginia.[2]
- Strauss et al. (2014)'s report, *Virginia and the Surging Sea: A vulnerability assessment with projections for sea level rise and coastal flood risk*, which assesses the vulnerability of systems to sea level rise and coastal flooding, including roads (all), local roads, secondary roads, state roads, and federal roads.[3]
- The *Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region* study, which evaluated the vulnerability of 63 counties and independent cities along coastal areas of Delaware, Maryland, New Jersey, New York, Pennsylvania, and Virginia to sea level rise.[4]
- Vulnerability studies from Hampton Roads, Virginia, including: *Climate Change in Hampton Roads: Impacts and Stakeholder Involvement (Phase I);*[5] *Climate Change in Hampton Roads, Phase II: Storm Surge Vulnerability and Public Outreach;*[6] and *Climate Change in Hampton Roads, Phase III: Sea Level Rise in Hampton Roads, Virginia.*[7]
- VDOT, the University of Virginia, Virginia Center for Transportation Innovation and Research (VCTIR), HRPDC, and Hampton Roads Transportation Planning Organization (HRTPO) *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot*, which assesses the impacts of climate change on transportation infrastructure in the Hampton Roads region.[8]
- The Hampton Roads Metropolitan Planning Organization *Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads,* which determined where flooding is expected on roadways, structures, and tunnels within in the Hampton Roads Metropolitan Planning Area by 2045 as a result of relative sea level rise and storm surge.[9]
- The Accomack-Northampton Planning District Commission *Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment*, which evaluates the risk of flooding due to sea level rise on transportation infrastructure (primary and secondary roads, structures, causeways, railroad, culverts and ditches, signalization infrastructure, and utilities and right-of-way).[10]
- The Northern Virginia Regional Hazard Mitigation Plan *Vulnerability Assessment* uses FEMA HAZUS software to estimate losses from hurricane winds and earthquakes. The study qualitatively assessed risks for identified hazards in local communities.[11]
- Metropolitan Washington Council of Governments' report on *Climate Change Adaptation in the Metropolitan Washington Region: Draft Transportation Sector Vulnerabilities*, which aims to identify possible impacts of climate change to the transportation sector.[12]

[1] Virginia Department of Emergency Management. 2018. Commonwealth of Virginia Hazard Mitigation Plan.

[2] Center for Coastal Resources Management, Virginia Institute of Marine Science (VIMS), and William & Mary. 2013. Recurrent Flooding Study for Tidewater Virginia.

[3] Strauss, B., C. Tebaldi, S. Kulp, S. Cutter, C. Emrich, D. Rizza, and D. Yawitz. 2014. Virginia and the Surging Sea: A Vulnerability Assessment with projections for sea level rise and coastal flood risk. Climate Central Research Report, pp. 1-29.

[4] Colgan, Charles S., Juliano Calil, Hauke Kite-Powell, Di Jin, and Porter Hoagland. 2018. Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region. Middlebury Institute of International Studies at Monterey.

[5] Hampton Roads Planning District Commission. 2010. Climate Change in Hampton Roads: Impacts and Stakeholder Involvement.

[6] Hampton Roads Planning District Commission. 2011. Climate Change in Hampton Roads, Phase II: Storm Surge Vulnerability and Public Outreach.

[7] Hampton Roads Planning District Commission. 2012. Climate Change in Hampton Roads, Phase III: Sea Level Rise in Hampton Roads, Virginia.

[8] Virginia Department of Transportation (VDOT), University of Virginia, Hampton Roads Planning District Commission (HRPDC). 2012. *Assessing Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot.*

[9] Hampton Roads Transportation Planning Organization. 2016. Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads.

[10] Accomack – Northampton Planning District Commission. 2015. Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment. Virginia Coastal Zone Management Program.

[11] Northern Virginia Regional Hazard Mitigation Plan. Vulnerability Assessment.

[12] Metropolitan Washington Council of Governments. Climate Change Adaptation in the Metropolitan Washington Region: Draft Transportation Sector Vulnerabilities.

1-B.3. Exposure Data and Timelines

The studies reviewed employed a range of exposure data, including various sea level rise and storm surge projections and inland/riverine flooding data. The sea level projections used in the *Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region* study are shown in Table 4-1, which represent the most comprehensive and recent studies. These projections are commonly used in coastal vulnerability assessments.

Table 1-B-3: Sea Level Scenarios for Virginia

Study	Variables Considered	Sea Level Rise Scenarios
2017 – ADAPT-VA: *Sea Level in Virginia, Historic Data and Projections*[1]	**GMSL Sea Level Rise Factors:** Thermal Expansion Ice Sheet Mass Changes Glacier mass changes **Local Sea Level Rise Factors:** Land subsidence	**2100 Projections** Low: 1.9 ft. Medium Low: 2.5 ft. Medium: 4.2 ft. Medium High: 5.8 ft. High: 7.5 ft. Extreme: 9.1 ft.
2013 – Recurrent Flooding Study for Tidewater Virginia[2]	**GMSL Sea Level Rise Factors:** Factors included in NCA report (2012): Ocean thermal expansion Ice melt **Local Sea Level Rise Factors:** Land subsidence	**2033-2063:** 1.5 ft. **2100:** Low: 3.2 ft. High: 5.5 ft. Highest: 7.5 ft.

As part of the *Recurrent Flooding Study for Tidewater Virginia*, VIMS developed sea level rise scenarios for Virginia by using the four scenarios developed by the National Climate Assessment and modifying them with land subsidence estimations for southeastern Virginia. In the future, land subsidence rates are anticipated to remain relatively constant (2.7 millimeters/year or 0.1 inch/year) while rates of sea level rise are expected to increase. Figure B-1 shows the sea level rise projections adjusted for southeastern Virginia.

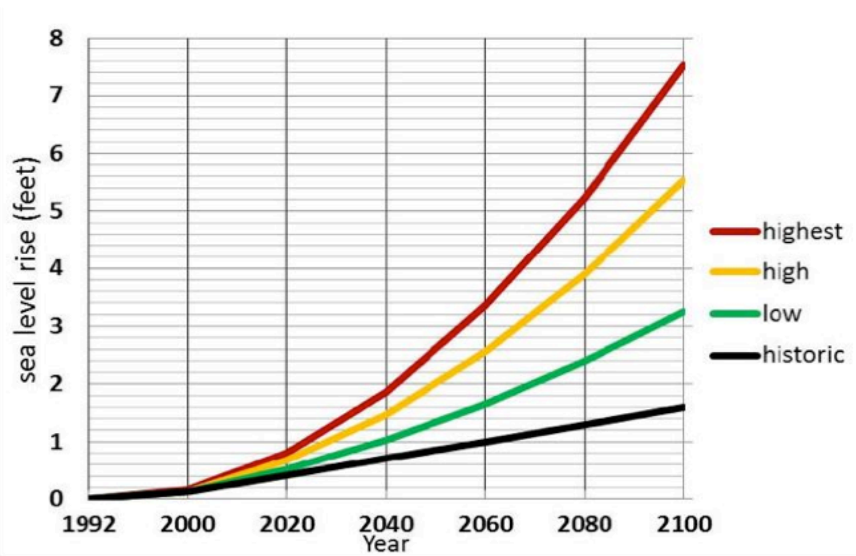


Figure 1-B-1: Sea Level Rise Projections for Southeastern Virginia

The Virginia and the Surging Sea study used data on projected local sea level rise based on Tebaldi et al. (2012)[3] and models and scenarios that NOAA prepared for the National Climate Assessment (Parris 2012).[4] For Virginia, local sea level rise is projected to be 1.2 to 1.5 feet by 2050 and 4.0 to 4.8 feet by 2100, based on a 2012 baseline. The study also used statistics on historical extreme water level patterns combined with projected sea level rise, and high-resolution, high-accuracy laser-based elevation data from the National Elevation Dataset.Additional Laser Imaging Detection and Ranging (system) (LIDAR) data was commissioned for southeast Virginia by the U.S. military and published by the U.S. Geological Survey.

[1] ADAPT Virginia. 2017. Virginia Sea Level.

[2] Mitchell, Molly, Carl Hershner, Herman Julie, Dan Schatt, Pam Mason, and Emily Eggington. 2013. "Recurrent Flooding Study for Tidewater Virginia." Virginia Institute of Marine Science, Center for Coastal Resources Management, William and Mary. doi:10.21220/V5TG79.

[3] Tebaldi, C., Strauss, B. H., & Zervas, C. E. (2012). "Modelling sea level rise impacts on storm surges along US coasts." Environmental Research Letters,7(1), 014032.

[4] Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss (2012). "Global Sea Level Rise Scenarios for the US National Climate Assessment." NOAA Tech Memo OAR CPO-1. 37 pp.

The *Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads* study involves mapping the potentially submerged areas under three scenarios using the best available elevation data:

- Scenario 1: 2.0 feet relative sea level rise
- Scenario 2: 2.0 feet relative sea level rise + 25-year storm surge
- Scenario 3: 2.0 feet relative sea level rise + 50-year storm surge

The *Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment* used four sea level rise projections from the VIMS 2013 study in combination with local subsidence rates (see Table B-4).

Table 1-B-4: Sea Level Rise Scenarios for the Eastern Shore

Sea Level Scenario above MHHW	Projected Date of Occurrence
1 foot	= 2025-2050
2 feet	= 2045-2090
3 feet	> 2060
4 feet	> 2070
5 feet	> 2080
6 feet	> 2090
Note: Projections from the VIMS Recurrent Flooding Study for Tidewater Virginia (2013) and adjusted for local subsidence rate for Wachapreague, VA (1.6 mm/year) based on Holmdahl and Morrison (1974).	

HRPDC completed three studies of vulnerability in the region. The assessments include elevation data from the National Elevation Dataset referenced to the North American Vertical Datum of 1988. HRPDC used a data set developed by the U.S. EPA to modify this data set to reflect local tidal conditions, since LiDAR was not available.[1] Projections for future sea level rise are based on equations from the 1987 National Research Council (NRC) report[2] and USACE guidance.[3] Historical sea level trends are from NOAA's Tides & Currents service. The three sea level rise scenarios are based on current rates of sea level rise – a low, an intermediate, and a high scenario (Table B-5).

Table 1-B-5: Projected Sea Level Rise at Hampton Roads Water Level Stations, 2010-2100 (in meters)

Station	Low Scenario	Medium Scenario	High Scenario
Chesapeake Bay Bridge Tunnel	0.45	0.76	1.74
Gloucester Point	0.37	0.68	1.65
Kiptopeke	0.32	0.63	1.61
Portsmouth	0.34	0.65	1.62
Sewell's Point	0.39	0.70	1.67

The *Commonwealth of Virginia Hazard Mitigation Plan* determined flood probability based on the designated zones in Flood Insurance Rate Maps and determined risk based on whether assets are within established FEMA flood zones.

1-B.4. Assessment Approaches

The majority of studies reviewed completed an exposure analysis of sea level rise, storm surge, or inland/riverine flooding hazards. For example:

- The *Commonwealth of Virginia Hazard Mitigation Plan* profiles 13 hazards, including flooding, and then assesses vulnerabilities due to hazards and estimates the potential losses to populations and property.
- The *Recurrent Flooding Study for Tidewater Virginia* report uses historical records of past inundation, as well as potential future flooding based on topographic mapping. In order to determine which assets could be exposed to flooding, the

[1] Titus, James G., and Jue Wang. 2008. Maps of Lands Close to Sea Level along the Middle Atlantic Coast of the United States: An Elevation Data Set to Use While Waiting for LIDAR. United States Environmental Protection Agency.

[2] National Research Council. 1987. *Responding to Change in Sea Level: Engineering Implications.* Washington, D.C. National Academy Press.

[3] U.S. Army Corps of Engineers. 2011. "Sea Level Change Considerations for Civil Works Programs." 1165-2-212. Washington, D.C.

study uses elevation maps and land use layers from the Coastal Change Analysis Program (C-CAP), which is a national standardized dataset of land cover and land use change that was developed through remotely sensed imagery.

- The *Virginia and the Surging Sea* study computes the length of each feature on land below a chosen water level to determine potential vulnerability.
- The *Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads* study aimed to determine where flooding is expected on roadways, structures, and tunnels within the Hampton Roads Metropolitan Planning Area by 2045 as a result of relative sea level rise and storm surge. The study uses HRPDC GIS elevation data from the most recent and highest resolution LiDAR data (which became available after the completion of vulnerability assessment studies by the HRPDC). The roadway dataset used is the road centerline database from the Virginia Geographic Information Network (VGIN). These maps are combined to identify segments of roadways that could be exposed under the different flooding scenarios.

A limited number of studies went beyond an initial exposure analysis to determine vulnerability based on additional factors. For example:

- The *Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region* study uses a GIS model to overlay NOAA's sea level rise data for two sea level rise scenarios (3 feet and 6 feet) with socio-economic indicators (population, housing units, total employment, summer employment, summer housing, infrastructure, ocean economy employment, social vulnerability, and fishing community vulnerability) in order to determine the areas with highest and lowest levels of vulnerability.
- HRPDC completed three studies that included a range of vulnerability assessment activities. The study team developed a GIS tool that combined storm surge data, elevation, and socio-economic data on critical infrastructure, population, roads, and businesses. The work completed under the studies utilized the GIS tool to analyze the effects of sea level rise on various sectors, including the built environment and infrastructure, and provide recommended adaptation measures. The map-based exposure analysis identifies areas vulnerable to inundation and which assets could be exposed using NOAA's Coastal Inundation Mapping process. The assessment includes:
  - Elevation data from the National Elevation Dataset referenced to the North American Vertical Datum of 1988. HRPDC used a dataset developed by the U.S. EPA to modify this data set to reflect local tidal conditions, since LiDAR was not available.[1]
  - Projections for future sea level rise based on equations from the 1987 NRC report[2] and USACE guidance.[3]
  - Inundation maps based on projected sea level rise using GIS that overlay with maps of transportation infrastructure. VDOT's road centerline database is used as the base data to evaluate infrastructure risk. Roads are categorized as interstate, primary, secondary, and local or private using VDOT's classification system. To create the final evaluation of exposed roadways, roads vulnerable under each of the three scenarios were identified and the length of each exposed segment was calculated in miles. Total length of exposed road was summed by category for each locality and the region as a whole.
- *The Vulnerability and Risk of Climate Change Effects on Transportation Infrastructure: Hampton Roads Virginia Pilot* assesses the impacts of climate change on transportation infrastructure in the Hampton Roads region. The report also includes recommendations on how to set priorities and reprioritize investments in the long-range transportation planning process. The key elements of the pilot were: (1) identifying the interactions between climate change and other factors such as economic recession, increased government regulation, maintenance/repair of existing infrastructure, technological innovation, and ecological degradation; (2) establishing the connection between these combinations of scenarios and transportation strategic planning; and (3) prioritizing limited resources such that an optimal allocation and timely intervention can be achieved. The project uses multicriteria decision analysis to perform the risk assessment. The majority of data input are from the 2034 long-range plan for HRTPO. Other data for climate scenarios were obtained through stakeholder sessions.

[1] Titus, James G., and Jue Wang. 2008. Maps of Lands Close to Sea Level along the Middle Atlantic Coast of the United States: An Elevation Data Set to Use While Waiting for LIDAR. United States Environmental Protection Agency.

[2] National Research Council. 1987. *Responding to Change in Sea Level: Engineering Implications.* Washington, D.C. National Academy Press.

[3] U.S. Army Corps of Engineers. 2011. "Sea Level Change Considerations for Civil Works Programs." 1165-2-212. Washington, D.C.

- The *Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment* completed both a regional inundation vulnerability assessment and a community and critical facility accessibility assessment. The study mapped local sea level rise projections, critical facilities and communities to determine how they would be impacted.

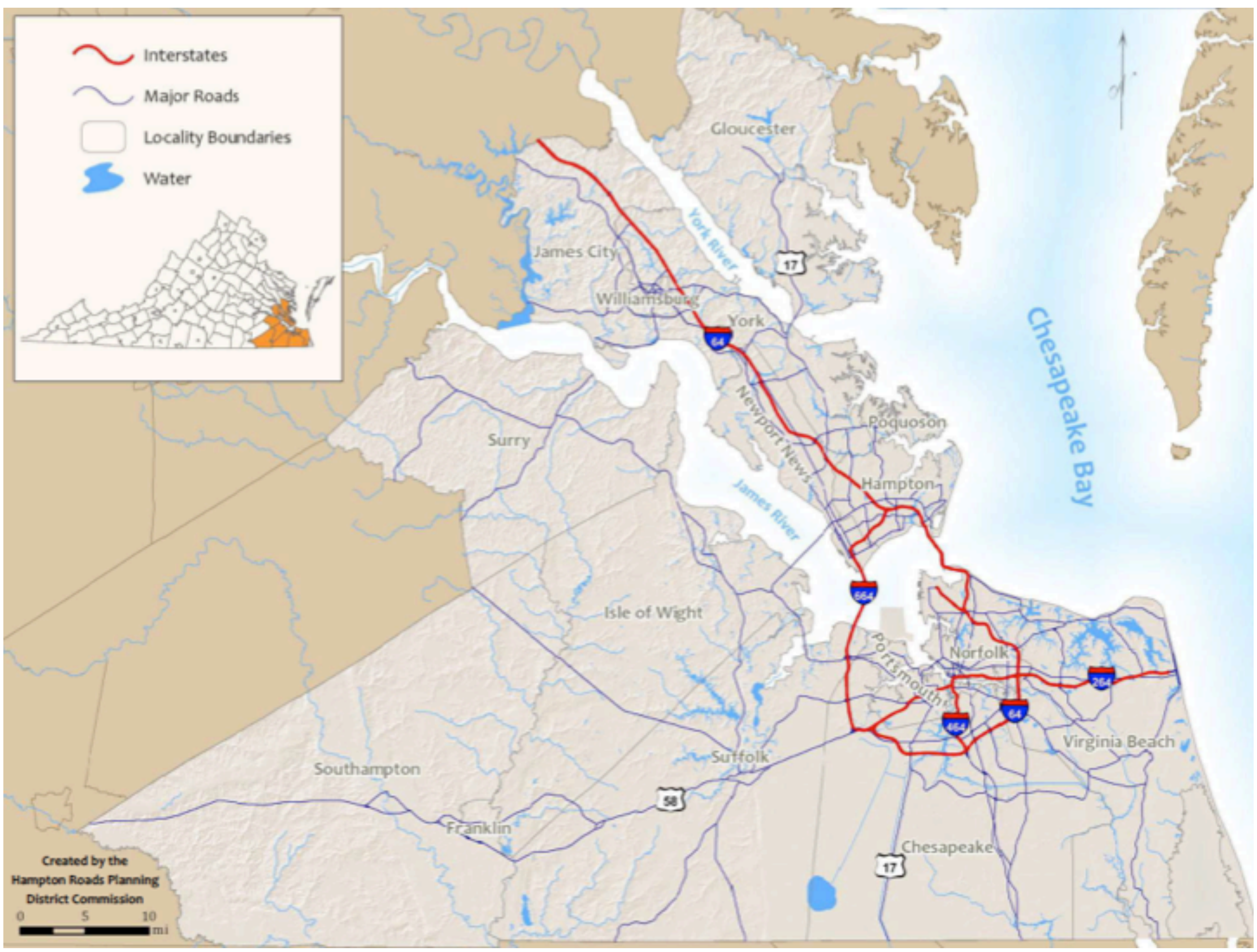
1-B.5. Key Findings

These studies include a range of key findings regarding sea level rise, storm surge, and inland/riverine flooding impacts to infrastructure in Virginia. For example, the *Recurrent Flooding Study for Tidewater Virginia* report concluded that sea level rise and storm surge is projected to lead to flooding of evacuation routes, increased hydraulic pressure on tunnels, and alteration of drainage capacity. Across 40 localities, 1,508 miles of road could be flooded by 1.5 feet of sea level rise and a 3-foot storm surge. In addition, navigation capacity may change, airport runways adjacent to tidal waters could be at risk due to storm surge flooding events, and railroads across marshes, swamps, or other low-lying land could also be impacted by sea level rise.

The *Virginia and the Surging Sea* report indicates that 1,469 miles of road lie below 5 feet of elevation in the state and more than 4,500 miles of road are below 9 feet. The *Climate Change Vulnerabilities in the Coastal Mid-Atlantic Region* study found that, within Virginia, a 3-foot scenario exposes 24 miles of major road and 4.6 miles of rail to flooding. The 6-foot scenario exposes 30.4 miles of roads and 29.1 miles of rail lines. Hampton City in Virginia shows up as the most vulnerable in the 3-foot scenario for major roads.

A number of studies have focused on the Hampton Roads area. Figure B-2 shows the Hampton Roads region.

Figure 1-B-2: Map of Hampton Roads Region



HRPDC completed three studies that found over 5,000 linear miles of road are exposed during Category 4 hurricanes. The studies found that a significant amount of transportation infrastructure in the region is potentially at risk of inundation due to sea level rise. Even with one meter of sea level rise above Spring High Tide, a large portion of the region's transportation infrastructure could be exposed to flooding, including 18 miles of interstate highways, 77 miles of state primary roads, 100 miles of secondary roads, and 684 miles of local and private roads.

The *Sea Level Rise and Storm Surge Impacts to Roadways in Hampton Roads* study identifies segments of roadways that could be exposed under the different flooding scenarios. For planned roads in the 2045 Analysis Network, structures and elevated structures are not included, as the team used aerial photographs to identify which structures were misidentified. This was not done for existing infrastructure. The study summarized submergence risks for centerline miles flooded by 2045 by jurisdiction for three sea level rise and storm surge scenarios (see Figure B-6).

Table 1-B-6: Potential Submerged Area of Roadways in Hampton Roads by 2045

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

*Centerline miles are cumulative for Scenarios 2 and 3. For example, Scenario 2 includes roadway segments from Scenarios 1 and 2. Scenario 3 includes roadway segments from Scenarios 1, 2, and 3.
**Existing Local Roadways include all other roadways not included in the 2045 Analysis Network, such as local and collector streets, ramps, and roads on military installations.

Based on the 2045 Analysis Network, only 0.1% (2.4 centerline miles) of the network is expected to be submerged with 2 feet of sea level rise. However, 5.9% (93.7 centerline miles) and 7.6% (119.8 centerline miles) of the network is expected to be submerged under more severe sea level rise and storm surge scenarios.

The *Eastern Shore of Virginia Transportation Infrastructure Inundation Vulnerability Assessment* identifies 33 miles of roads in the region that could be vulnerable to inundation between 2025 and 2050 with one foot of relative sea level rise. The number increases to 371 miles, or 24.5% of all roads vulnerable, as early as 2090 with six feet of relative sea level rise. The rail yard at Cape Charles is the only section of railway potentially vulnerable to inundation by the end of the century.

1-B.6. Utilization of Vulnerability Assessment

State and local transportation agencies around the nation are assessing their vulnerabilities to climate change. Many agencies have conducted vulnerability assessments that aim to illuminate in what ways their transportation systems will be impacted. Following the vulnerability assessments, many have considered or taken additional steps to use and integrate the vulnerability scores into their work (i.e., mainstreaming) or to continue refining their understanding of their vulnerabilities.

Mainstreaming vulnerability assessments into agency practices is a productive way to build resilience over time. Some DOTs (e.g., Maryland SHA, Florida District 4) are developing strategic plans to outline a strategy for incorporating vulnerability assessments into all aspects of their work. The use and integration of vulnerability scores are categorized into the following predominant buckets:

- Integrate vulnerability scores into asset management planning.
- Integrate vulnerability considerations into maintenance and operations planning.
- Utilize vulnerability scores in project design, development, and review.
- Strengthen coordination and collaboration across the agency and with stakeholders.

Each of these areas is briefly described below with one or two illustrative examples with more details in Table B-7.

1-B.6.1. Asset Management Planning

In integrating vulnerability scores into asset management, agencies aim to optimize the performance and cost-effectiveness of transportation facilities as the climate changes.

- Following their vulnerability assessment, the Maryland Department of Transportation (MDOT) sought to update its pavement performance models to reflect current and expected inundation frequency for sea level rise-related temporary flooding events.[1]
- Ohio DOT is incorporating climate change considerations into their lifecycle planning workflows.
- Given the federal requirement to consider climate change in asset management planning, many state DOTs are using their vulnerability assessments to inform the risk register ratings for climate change and their overall risk management plan.
- Note that FHWA is expected to release a handbook on considering climate change in asset management planning.

1-B.6.2. Maintenance and Emergency Management Planning

Agencies are considering nuanced maintenance and operations approaches that consider the impacts of intensified environmental hazards. These approaches include proactive preparation of infrastructure in advance of forecasted weather events (focused on areas with historical impacts), updated emergency response plans, and updates to maintenance monitoring and tracking systems to better capture current impacts of weather on system performance and condition.

- The Kentucky Transportation Cabinet (KYTC) planned to apply their vulnerability assessment towards developing maintenance activities that proactively prepared infrastructure for severe weather, such as extreme heat and precipitation events.[2]
- Mostly concerned about riverine flooding and extreme precipitation, the Iowa Department of Transportation (Iowa DOT) planned to integrate vulnerability scores into their maintenance monitoring and tracking systems.[3]
- Iowa DOT has also developed a robust real-time flood monitoring/modeling system to provide advance notice of roadway overtopping and the potential for bridge scour.[4]
- The Massachusetts Department of Transportation (MassDOT) expressed intent to update their emergency response plans with the findings from their vulnerability assessment (e.g., ensuring planned detour routes are not also at risk of flooding from coastal storms).[5]

[1] Maryland Department of Transportation State Highway Administration. Integrating Extreme Weather and Climate Risk into MDOT SHA Asset Management and Planning. 2019. https://www.fhwa.dot.gov/asset/pilot/md.pdf

[2] Kentucky Transportation Cabinet. Asset Management, Extreme Weather, and Proxy Indicators. 2019. https://www.fhwa.dot.gov/asset/pilot/ky.pdf

[3] Iowa Department of Transportation. FHWA Climate Resilience Pilot Program. 2015. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/iowa/index.cfm

[4] Iowa FOT. https://iowadot.gov/systems_planning/freight/FAC/Sept2019/Infrastructure-Design-and-Construction-to-Improve-Resiliency.pdf

[5] Massachusetts Department of Transportation. FHWA Climate Resilience Pilot Program. 2015. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/connecticut/index.cfm

1-B.6.3. Project Design, Development, and Review

As projects are proposed, agencies that conducted vulnerability assessments are examining how to flag their findings for use during project design, development, and review. This can include integrating the vulnerability results into existing internal GIS databases and requiring the information to be considered at some step in the project development process (e.g., project initiation, environmental review) and efforts such as updating design standards/guidelines.

- Massachusetts DOT integrated their vulnerability findings into their Massachusetts Project Intake Tool (MaPIT), which is a required three-step process for project initiation.[1]
- Maine DOT integrated climate-related questions that can be answered using their vulnerability assessments results into their early environmental review screening. They also integrated sea level rise into their preliminary design guidance.[2]
- Washington DC Department of Energy and Environment (DOEE) used vulnerability scores of projected extreme temperatures and precipitation events to update design standards for roads and transit infrastructure.[3]
- The Oregon Department of Transportation (ODOT) described using their vulnerability scores and sea level rise mapping to develop project review guidance.[4]
- Washington DOT has developed guidance for project-level climate change evaluations (as well as planning-level guidance).[5]
- If desired, ICF can provide a list of state DOTs that we know have updated their design standards/manuals to incorporate climate change.

1-B.6.4. Internal and External Communication

A major component of the vulnerability assessments produced by other state and municipal transportation agencies is data collection and sharing. Communication works in tandem with data accessibility. Agencies used their data findings to communicate the vulnerability of their transportation systems to those outside their organization. This includes providing webinars and training on the vulnerability information to DOT Districts to inform their annual work plans, and to local municipalities for use in project proposals.

- The Texas Department of Transportation (TxDOT) proposed increasing internal collaboration between transportation engineers and hydrologists to use the vulnerability scores to inform their efforts.[6]
- Caltrans developed a Climate Change Communication Guide to educate, inform, and strengthen communication both internally and with external partners and the public.[7]
- An emerging conversation at the national scale is the role of DOTs in guiding discussions with municipalities about managed retreat from areas that will be permanently inundated by sea level rise.[8]
- Massachusetts DOT significantly contributed to the development of their Integrated State Hazard Mitigation and Climate Adaptation Plan.[9]
- Many DOTs have established internal resiliency working groups to regularly discuss the topic and coordinate their resilience efforts.
- Many DOTs have also used "lunch and learns" or other training venues to communicate to many staff members how climate change is relevant to their work and provide resources for more information.

[1] Massachusetts DOT. https://www.mass.gov/info-details/massdot-highway-initiating-a-project

[2] Maine DOT. https://www.maine.gov/mdot/bdg/docs/BDGupdateJune2018.pdf

[3] Department of Energy and Environment. Climate Adaptation Plan. 2016. https://doee.dc.gov/sites/default/files/dc/sites/ddoe/publication/attachments/AREA_Climate_Adaptation_Plan_ForScreen_2016-11-11.pdf

[4] Oregon Department of Transportation. FHWA Climate Resilience Pilot Program. 2015. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/oregon/index.cfm

[5] Washington DOT. https://wsdot.wa.gov/environment/technical/disciplines/air-quality-noise-energy/addressing-climate-change

[6] Texas Department of Transportation. Asset Management, Extreme Weather, and Proxy Indicators Pilot Final Report. 2019. https://www.fhwa.dot.gov/asset/pilot/tx.pdf

[7] Caltrans. Climate Change Communication Guide. 2020. https://dot.ca.gov/-/media/dot-media/programs/transportation-planning/documents/caltransclimatecommunicationguidepdf-a11y.pdf

[8] TRB. http://www.trb.org/Main/Blurbs/181784.aspx

[9] Massachusetts. Integrated State Hazard Mitigation and Climate Adaptation Plan https://www.mass.gov/service-details/massachusetts-integrated-state-hazard-mitigation-and-climate-adaptation-plan

1-B.6.5. Funding

Some DOTs are exploring ways that their vulnerability assessment results can be used to access funding for resilience projects.

- The FHWA Emergency Relief program allows for resilience upgrades to be made if an economic case can be made for it. Some DOTs are considering using their vulnerability assessment results to help inform whether or not they should try to make the case for a betterment.[1]
- DOTs are also preparing for more resilience-focused funding (either discretionary or by formula) and are using their vulnerability assessment results and other inputs to develop a list of top resilience project ideas.
- Some DOTs applied for FEMA Building Resilient Infrastructure and Communities (BRIC) grants.[2]
- To further drive the economic benefit of resilience, some DOTs are converting their vulnerability findings into illustrative economic impacts (e.g., vehicle hours of delay if all roads highly vulnerable to sea level rise were flooded for just one week a year).
- Others are conducting risk-based corridor assessments using the RAMCAP methodology, which estimates the economic risk of inaction. This is a very data intensive approach and is not well suited to a state-wide assessment, but can be very useful for building the case for investment in select corridors.[3]

1-B.6.6. Defining Performance Measures

Resilience performance measures are an emerging area of work. Due to the sporadic nature of extreme weather events, it can be difficult to accurately measure resilience over time. An NCHRP RFP to address this topic is expected to be released in the coming year.

1-B.6.7. Asset-Specific and Corridor Level Analyses

Vulnerability assessments can be conducted at a range of scales, including district-level, corridor level, and asset-specific. Corridor and asset-specific scales can allow for a more in-depth, engineering focused review of risks (i.e., moving beyond an indicator-based approach).

- The Tennessee Department of Transportation proposed conducting more detailed vulnerability assessments for their specific critical assets that are indicated as highly vulnerable.[4]
- Caltrans is conducting a Planning and Environmental Linkages study for a section of SR 37 that is vulnerable to sea level rise.[5]
- Some state DOTs (e.g., Massachusetts[6], Iowa) have invested in robust modeling to better understand the extent of future inland floodplains.

Table 1-B-7: Actions Based on Vulnerability Assessment: Summary of Literature Review

Hazard	General Area of Action	Geography	Action
Maryland Department of Transportation[7]			
Storm surge, SLR	Planning	Region	Identify and integrate the vulnerability assessment results into existing MDOT SHA asset management, planning, and processes
Storm surge, SLR	Maintenance	Region	Update pavement performance models to reflect current and expected inundation frequency

[1] FHWA. https://www.fhwa.dot.gov/specialfunding/er/191011.cfm

[2] FEMA. https://www.fema.gov/grants/mitigation/building-resilient-infrastructure-communities

[3] Colorado DOT. I-70 Corridor Risk & Resilience Pilot. 2017. https://www.codot.gov/programs/planning/assets/plans-projects-reports/reports/i70rnr_finalreport_nov302017_submitted_af.pdf

[4] Tennessee Department of Transportation. FHWA-HEP-16-076. 2015. https://www.fhwa.dot.gov/environment/sustainability/resilience/pilots/2013-2015_pilots/tennessee/index.cfm

[5] Caltrans. https://dot.ca.gov/-/media/dot-media/district-4/documents/37-corridor-projects/sr-37_swg_11_16_20_pdf_notes-2020-12-16.pdf

[6] MassDOT. https://www.mass.gov/info-details/climate-change-resiliency#coastal-flood-exceedance-probability-maps-

[7] Maryland Department of Transportation. Integrating Extreme Weather And Climate Risk Into MDOT SSHA Asset Management And Planning.

Hazard	General Area of Action	Geography	Action
Storm surge, SLR	Design	Asset	Create and implement a process to screen any new structures projects for climate risk
Storm surge, SLR	Design	Asset	Incorporate climate risk into the project Purpose and Need
Storm surge, SLR	*Capacity building*	*Region*	*Create a climate risk data viewer and disseminate climate risk data throughout the agency and its partners*
Storm surge, SLR	Maintenance	Asset	Calculate and provide the percentage of time different road segments may be inundated (to inform pavement performance modeling).
Storm surge, SLR	Maintenance	Asset	Provide information on the impacts of inundation on pavement performance (to inform pavement performance modeling).
Storm surge, SLR	Awareness, capacity building	Region	Make climate risk information available to District, Operations, MPOs, counties and municipalities, as well as other state agencies.
Storm surge, SLR	Planning	Region	Add climate risk fields (e.g., pavement inundation frequency, HVI) into the PMS to inform lifecycle planning
Storm surge, SLR	Planning	Region	Update PMS performance models to reflect current and expected inundation frequency.
Storm surge, SLR	Operations	Region	Systematize collection of road and bridge closure information associated with flooding.
Storm surge, SLR	Planning	Region	Include a field for the HVI score in bridge vulnerability results in CCVV to indicate vulnerability of the bridge approach.
Storm surge, SLR	Design	Region	Develop a review process for considering risks related to future environmental conditions in project planning.
Storm surge, SLR	Planning	Region	MDOT SHA to apply review process for considering risks related to future environmental conditions in project planning.
Storm surge, SLR	Planning	Region	Office of Planning and Preliminary Engineering (OPPE) to incorporate bridge vulnerability results into CCVV.
Storm surge, SLR	Planning	Region	OOS to consult CCVV in project planning process.
Storm surge, SLR	Planning	Region	Improve modeling of precipitation change effects on flood zones.
Storm surge, SLR	Operations	Region	MDOT SHA to systematize collection of bridge closure information associated with flooding.
Storm surge, SLR	Design	Asset	Develop guidance regarding project development strategies for various sub-categories of assets that take climate risk information into account.
Storm surge, SLR	Planning	Region	OPPE to review CCVV and document project adaptation in environmental review (e.g., National Environmental Policy Act (NEPA) processes).
Storm surge, SLR	Capacity building	Region	OPPE to finalize CCVV and share with counties.
Storm surge, SLR	Capacity building	Region	OPPE to share CCVV at standing OHD and OPPE coordination meetings.
Storm surge, SLR	Capacity building	Region	OPPE to share CCVV with all Districts.

Hazard	General Area of Action	Geography	Action
Storm surge, SLR	Awareness, capacity building	Region	OPPE to hold a "lunch and learn" series to share CCVV, availability of climate risk information. Participants may include Bridge Hydraulics and Highway Hydraulics, among others.
Storm surge, SLR	Planning	Region	PPE to incorporate climate risk into Purpose and Need template, which is completed to justify all new projects
Storm surge, SLR	Planning	Region	OPPE to update project management manuals or checklists to include the climate risk results as resource materials for consideration during project development and management.
Storm surge, SLR	Planning	Region	OPPE to integrate climate risks into MOSAIC, a quantitative tool used to estimate the impact of multimodal highway corridor improvement options on sustainability in the transportation planning process
Storm surge, SLR	Awareness	Region	OPPE to provide climate risk data to discretionary grant applicants.
Storm surge, SLR	Planning	Region	MDOT SHA to develop decision trees and other guidance on climate risk management
Storm surge, SLR	Operations	Region	Provide CHART with a "cheat sheet" for how to interpret the different flood extent layers.
Storm surge, SLR	Operations	Region	CHART, District Maintenance, and Office of Maintenance to consult CCVV to inform preparations for flood events.
Storm surge, SLR	Planning	Region	Continue to include climate-related risks in the overall TAMP risk register.
Storm surge, SLR	Capacity building	Region	OPPE to share statewide climate risk statistics with OMT and OOS related to TAMP risk register items.
Storm surge, SLR	Planning	Region	Incorporate climate risk considerations throughout TAMP.
Storm surge, SLR	Planning	Region	Improve and finalize the online interactive CCVV, which includes HVI data, bridge vulnerability data, and related future flooding information.
Storm surge, SLR	Operations	Region	Implement a process for tracking flood-related road closures (e.g., road closure reporter).
Storm surge, SLR	Capacity building	Region	Continue to disseminate climate risk information through coordination meetings, lunch and learn meetings, and other venues.
Kentucky Transportation Cabinet[1]			
Extreme heat	Design	Asset	Incorporate the effects of projected warmer temperatures on pavement design and performance monitoring
Extreme heat, extreme precipitation	Planning	Region	Bringing projects into a central database and codifying records in GIS
Extreme heat, extreme precipitation	Planning	Region	Integrate vulnerability assessment into project prioritization scoring process
Extreme heat, extreme precipitation	Planning	Region	Incorporate extreme weather into asset management risk register
Extreme heat, extreme precipitation	Planning, awareness	Region	Bring together multiple data sources by KYTC to account for and communicate risks

[1] Kentucky Transportation Cabinet. Asset Management Extreme Weather, and Proxy Indicators.

Hazard	General Area of Action	Geography	Action
Extreme heat, extreme precipitation	Maintenance	Region	Develop KYTC maintenance activities that can proactively prepare for extreme weather
Extreme heat, extreme precipitation	Capacity building	Region	Establish a Resiliency Working Group
Extreme heat, extreme precipitation	Planning	Region, asset	Incorporate extreme weather into asset management and Transportation Asset Management Plan
Texas Department of Transportation[1]			
Inland flooding	Maintenance	Region	Work with hydrological models to refine risk assessments by adding additional spatial and temporal dimensions to analysis
Inland flooding	Capacity building	Region	Increase collaboration between transportation engineers and hydrologists to inform efforts
Inland flooding	Design	Region	Develop tools to analyze impacts of measures to increase pavement protections from flooding (i.e. flood walls, levees, pumping stations, wetland installation, green infrastructure)
Inland flooding	Planning, capacity building	Region	Incorporate results on a network level to support managerial decisions on flood event impacts
Inland flooding	Planning	Region	Develop a resilience index for the state-maintained system for both potential infrastructure damage and disruptive impacts
Metropolitan Transportation Commission[2]			
SLR	Planning	Subregion	Assess adaptation options to develop a regional and multi-modal adaptation plan
Extreme heat, drought, storms, inland flooding	Planning	Region	Development of a Resilience Pilot Program
California Department of Transportation, District 1[3]			
Extreme heat, extreme precipitation, SLR, inland flooding, coastal erosion, landslides	Capacity building	Subregion	Coordinate with public agencies and private landowners on adaptation planning
Extreme heat, extreme precipitation, SLR, inland flooding, coastal erosion, landslides	Planning, Design	Region	Consider updates to department planning and design policies to integrate climate change, such as in updating maintenance and repair data collection and tracking systems to collect data related to extreme weather
Connecticut Department of Transportation[4]			
Extreme precipitation, inland flooding	Planning	Region	Integrate results into existing databases and practices
Extreme precipitation, inland flooding	Capacity building	Region	Coordinate with federal, state, and local partners

[1] Texas Department of Transportation. Asset Management, Extreme Weather, and Proxy Indicators Pilot Final Report.
[2] FHWA Climate Change Vulnerability Assessment Pilot Project: Metropolitan Transportation Commission.
[3] FHWA Climate Resilience Pilot Program: California Department of Transportation District 1.
[4] FHWA Climate Resilience Pilot Program: Connecticut Department of Transportation

Hazard	General Area of Action	Geography	Action
Iowa Department of Transportation[1]			
Riverine flooding, extreme precipitation	Maintenance	Region	Integrate findings into monitoring and tracking systems for maintenance
Riverine flooding, extreme precipitation	Planning	Asset	Conduct additional asset-specific vulnerability assessments
Riverine flooding, extreme precipitation	Planning	Region	Develop guidelines on estimating impacts of larger flood events
Riverine flooding, extreme precipitation	Planning	Region	Utilize climate data in cost-benefit analysis
Maine Department of Transportation[2]			
Inland flooding, coastal erosion, SLR, storm surge	Planning	Region	Evaluate future projects using methodology from the vulnerability assessment
Inland flooding, coastal erosion, SLR, storm surge	Planning	Region	Pilot a benefit-cost analysis for inland corridors and associated climate hazards
Inland flooding, coastal erosion, SLR, storm surge	Planning, awareness	Region	Incorporate the results into management decisions
Inland flooding, coastal erosion, SLR, storm surge	Planning	Region	Make the case for additional funding resources for future flood vulnerability assessment and adaptation work
Massachusetts Department of Transportation[3]			
SLR, storms	Planning, awareness, capacity building	Subregion	Share the results with local officials
SLR, storms	Design	Region	Determine engineering feasibility behind implementing adaptations strategies
SLR, storms	Emergency management	Region	Update emergency response plans using the findings
SLR, storms	Maintenance	Region	Regularly update hydrodynamic models
Extreme precipitation, extreme heat	Capacity building	Region	Continued monitoring and capacity building efforts with MDOT partners
Extreme precipitation, extreme heat	Planning	Region	Integrating climate and resiliency goals into the state long range transportation plan
Extreme precipitation, extreme heat	Planning	Region	Developing methods to integrate climate adjusted benefit cost analysis into investment and programming decisions.
Extreme precipitation, extreme heat	Capacity building	Region	Investigate incorporating risk data into the Michigan Geographic Framework (statewide GIS framework) or otherwise provide access to current data within MDOT systems and to other partners.
Extreme precipitation, extreme heat	Operations	Region	Begin monitoring roadway closure frequency and duration in high-risk areas

[1] FHWA Climate Resilience Pilot Program: Iowa Department of Transportation
[2] FHWA Climate Resilience Pilot Program: Maine Department of Transportation
[3] FHWA Climate Resilience Pilot Program: Massachusetts Department of Transportation

Hazard	General Area of Action	Geography	Action
Extreme precipitation, extreme heat	Planning	Region	Coordinate with partner agencies to identify high-risk areas in state and local Multi-Hazard Mitigation Plans.
Extreme precipitation, extreme heat	Capacity building	Region	Establish a climate resiliency working group to track progress and challenges of integrating climate risk with asset management.
Extreme precipitation, extreme heat	Planning	Region	Incorporate risk scores into Bridge Management System (BMS). Associate climate risk score for each bridge in the National Bridge Inventory, Pontis Bridge Inspection, and Structure Inventory and Appraisal reporting systems.
Extreme precipitation, extreme heat	Planning	Region	Evaluate the economic impacts of roadway closures in various parts of the state and establish thresholds for acceptable closure levels for various precipitation scenarios.
Extreme precipitation, extreme heat	Planning	Region	Conduct a more in-depth evaluation of the use of pump infrastructure to determine if additional capacity can be generated or if additional investment is feasible
Extreme precipitation, extreme heat	Operations	Region	Begin tracking extreme weather-related disruptions to seasonal construction days. Adjust guidelines for construction practices.
Extreme precipitation, extreme heat	Design	Region	Over time, identify design modifications or thresholds (or other adaptation strategies) to reduce long term vulnerability
Extreme precipitation, extreme heat	Maintenance	Region	Incorporate climate risk scores for extreme heat into Road Quality Forecast System (RQFS) and Remaining Service Life (RSL) strategies. Begin monitoring performance relative to standard reconstruction and rehabilitation timeframes.
Extreme precipitation, extreme heat	Planning	Region	Conducting more detailed corridor studies that help focus and refine the statewide risk analysis
Extreme precipitation, extreme heat	Planning	Region	Integrate findings into asset management programs
Minnesota Department of Transportation[1]			
Extreme precipitation, inland flooding	Planning	Region	Mainstream findings in long-range transportation planning
Extreme precipitation, inland flooding	Awareness, capacity building	Region	Undertake education/dialogue throughout the agency on the flooding/climate change issues and the methodology employed in this study
Extreme precipitation, inland flooding	Planning	Region	Use the results of this study to make the case for additional funding resources from the legislature for future flood vulnerability assessment and adaptation work.
Extreme precipitation, inland flooding	Awareness	Region	Share results of this work with other state and local agencies and establish a collaborative effort to better define and address risks
Extreme precipitation, inland flooding	Planning	Subregion, asset	Complete vulnerability assessments for all districts and other types of "assets", such as facility-level adaptation assessments
Extreme precipitation, inland flooding	Planning	Region	Test the sensitivity of vulnerability scoring to different criteria weighting

[1] FHWA Climate Resilience Pilot Program: Minnesota Department of Transportation

Hazard	General Area of Action	Geography	Action
New York Department of Transportation[1]			
Inland flooding	Planning	Region	Improve ongoing data collection on social, economic, and environmental benefits
Inland flooding	Planning	Region	Incorporate findings into decision making on projects and program selections
Inland flooding	Planning	Subregion	Test the scoring framework in other areas of the state
Oregon Department of Transportation[2]			
Extreme precipitation, inland flooding, SLR, landslides, coastal erosion	Planning	Region	Implement program for data monitoring and research at high-risk sites
Extreme precipitation, inland flooding, SLR, landslides, coastal erosion	Planning	Region	Develop project review guidance that uses SLR mapping
Extreme precipitation, inland flooding, SLR, landslides, coastal erosion	Capacity building, awareness	Region	Enhance interagency coordination on infrastructure protection and co-benefit projects.
Extreme precipitation, inland flooding, SLR, landslides, coastal erosion	Planning	Region	Screen highest-risk sites to lay the groundwork for a programmatic regulatory approach
Extreme precipitation, inland flooding, SLR, landslides, coastal erosion	Planning	Region	Integrate adaptation with other hazards resilience planning efforts, including investigating opportunities to prioritize adaptation planning for emergency routes
Extreme precipitation, inland flooding, SLR, landslides, coastal erosion	Operations		Standardize records of storm impacts on the transportation system
Extreme precipitation, inland flooding, SLR, landslides, coastal erosion	Planning	Region	Formalize detour routes for priority corridors
Tennessee Department of Transportation[3]			
Inland flooding, extreme heat, extreme precipitation, extreme cold, high winds	Planning	Asset	Conduct more detailed vulnerability assessments for specific critical assets that are highly vulnerable
Inland flooding, extreme heat, extreme precipitation, extreme cold, high winds	Awareness, capacity building	Subregion	Communicate site-specific results to local stakeholders

[1] FHWA Climate Resilience Pilot Program: New York State Department of Transportation
[2] FHWA Climate Resilience Pilot Program: Oregon Department of Transportation
[3] FHWA Climate Resilience Pilot Program: Tennessee Department of Transportation

Hazard	General Area of Action	Geography	Action
Thawing permafrost/ ice, landslides, extreme precipitation	Planning	Region	Findings used to inform incorporation of climate uncertainty and economic factors into transportation design and decision-making processes
Michigan Department of Transportation[1]			
Flooding	Planning	Region	Integrating risk scores into the transportation asset management plan (inventory and condition analysis, risk management process, call for projects)
	Planning	Region	Update the project scoping process to incorporate information from the Flooding Risk Tool and to collect enough information to adequately determine drainage issues with potential flooding mitigation strategies
	Operations	Region	Evaluate options for tracking flood-related closures or delay events as they occur.
Florida Department of Transportation[2]			
SLR, storm surge, coastal erosion, inland flooding, extreme precipitation, storms	Planning	Region	Identify and develop tailored adaptation strategies to enhance resilience
SLR, storm surge, coastal erosion, inland flooding, extreme precipitation, storms	Planning	Region	Perform multimodal assessments for master planning
SLR, storm surge, coastal erosion, inland flooding, extreme precipitation, storms	Planning	Region	Assess risks to detour routes for critical facilities
SLR, storm surge, coastal erosion, inland flooding, extreme precipitation, storms	Capacity building	Region	Create an internal crowd-sourcing data collection tool for better understanding existing areas with flood impacts.
SLR, storm surge, coastal erosion, inland flooding, extreme precipitation, storms	Awareness	Region	Share results with District offices.
SLR, storm surge, coastal erosion, inland flooding, extreme precipitation, storms	Planning	Region	Incorporate results into investment decision-making via the Strategic Investment Tool.
SLR, storm surge, coastal erosion, inland flooding, extreme precipitation, storms	Planning	Region	Integrate assessment outcomes into decision support systems (e.g., planning and programming, asset management, maintenance, emergency response, operations).
SLR, precipitation change, temperature change, fire risk	Planning	Region	Incorporate the climate change vulnerability assessment into investment decisions.

[1] Michigan Department of Transportation. Climate Resiliency and Flooding Mitigation Study

[2] Florida Department of Transportation. Technical Memorandum: Risk Assessment on SIS Facilities

Hazard	General Area of Action	Geography	Action
SLR, precipitation change, temperature change, fire risk	Awareness	Region	Analyze the results and conduct queries in GIS to show % of highways at risk. Communicate these to WSDOT programs and executive management.
SLR, precipitation change, temperature change, fire risk	Planning	Region	Develop a focused strategic plan to address long-term needs of key routes.
SLR, precipitation change, temperature change, fire risk	Planning, design, operations	Region	Integrate climate change projections as another input into planning, design, and operational programming.
Washington, DC Department of Energy and Environment[1]			
SLR, flooding	Planning	Region	Identify at-risk facilities and develop adaptation or retirement plans for those facilities, prioritizing upgrades based on the age and criticality of the assets as well as their vulnerability
SLR, flooding	Planning	Region	Identify at-risk facilities and develop adaptation or retirement plans for those facilities, prioritizing upgrades based on the age and criticality of the assets as well as their vulnerability
SLR, flooding	Operations, emergency management, awareness	Region	Conduct near-term (2020s) and long-term flooding (2050s+) evaluations for at-risk facilities based on projected increases in extreme precipitation and storm surges as well as permanent inundation due to sea level rise.
SLR, flooding	Planning, emergency management	Region	Identify alternate evacuation routes for roads and bridges identified as vulnerable to flooding and/or sea level rise.
Extreme heat, extreme precipitation	Design	Region	Update design standards for roads and transit infrastructure to account for projected extreme temperatures and extreme precipitation events. Ensure all street tree boxes are filled and that large shade trees are planted in tree boxes where possible.
Extreme heat, extreme cold	Design	Region	Evaluate existing bridges' expansion joints and design for resilience to extreme temperatures
SLR	Design	Region	Evaluate vertical clearance for bridges on waterways based on sea level rise projections.
Minnesota Department of Transportation[2]			
Flooding	Program	Region	Established Flood Mitigation Program ("Program") to increase the resilience of transportation system after severe spring floods in 2010 caused over $64 million in damages in the state. The Flood Mitigation Program will fund repairs, elevations, and realignments to road and bridges, as well as improvements to drainage structures. Although the program documents do not explicitly cite to climate change, MnDOT lists the Flood Mitigation Program as an adaptation action that the agency is taking to prepare for climate change.

[1] Washington, DC Department of Energy and Environment. Climate Adaptation Plan.

[2] Minnesota Department of Transportation. Flood Mitigation Program.

Appendix 1-C: Methodology for Creation of the Extreme Inland/ Riverine Flooding Scenario

One of the three scenarios for inland/rivering flooding relied on 500 year floodplain data and applied an additional buffer to create a scenario equivalent of extreme sea level rise, while limiting this buffer based on the width of the floodplain. This was done using the following GIS steps resulting in an additional buffer of 10-200 feet depending on width of the flood plain.

1. Generate negative-distance buffers at varying distances (25, 50, 100, 200, 300, 400, 500 feet) within the combined 100-year and 500-year floodplain area (Figure C-1). This is intended to capture areas that are more than 1,000 feet wide (see the dark blue below) all the way to 50 feet or less.

Figure 1-C-1: Generate Negative-distance Buffers

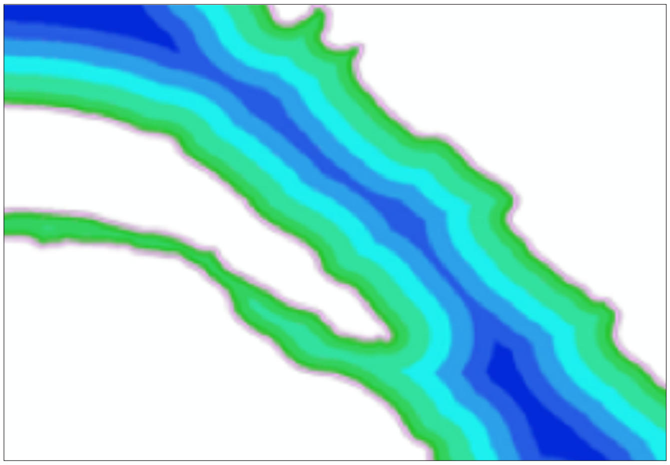
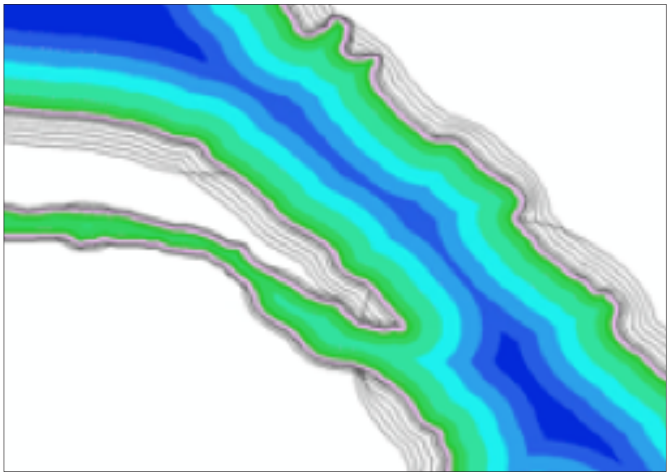


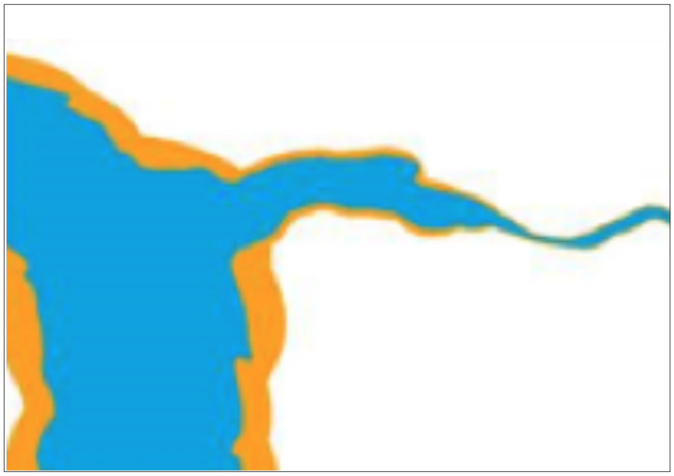
Figure 1-C-2: Apply Buffers



2. Apply buffers to these inner rings equivalent to the distance needed to get back out to the edge of the floodplain + 20% of width (Figure C-2). This is as follows:
   - More than 1,000ft wide areas (500ft dark blue inner rings) get buffered at 500 + 200ft
   - 800ft wide areas (400ft inner rings) get buffered at 400 + 160ft
   - 600ft wide areas (300ft inner rings) get buffered at 300 + 120ft
   - (continue the same method)
   - 50 ft wide areas (or less) get a minimum buffer of 10ft from edge of floodplain
3. Merge the buffers into one (Figures C-3 and C-4)

1-C-3: Merge Buffers (Sample 1)

1-C-4: Merge Buffers (Sample 2)



Buffer around 500 year floodplain

Appendix 1-D: Sea Level Rise Scenarios

The VTrans Vulnerability Assessment makes use of Year 2040 Intermediate, Intermediate High, and Extreme Scenario from NOAA. The sea level rise scenarios and their associated values are included as Figure D-1 and Table D-1 .

Figure 1-D-1: Relative Sea Level Rise Scenarios Curves[1]

Scenarios for SEWELLS POINT
NOAA2017 VLM: 0.00810 feet/yr
All values are expressed in feet

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17
2010	-0.09	0.03	0.06	0.13	0.19	0.29	0.29
2020	-0.00	0.26	0.33	0.46	0.62	0.75	0.82
2030	0.08	0.42	0.56	0.82	1.08	1.34	1.47
2040	0.16	0.65	0.82	1.21	1.61	2.06	2.29
2050	0.24	0.85	1.05	1.64	2.23	2.95	3.34
2060	0.32	1.08	1.31	2.13	2.95	3.97	4.62
2070	0.40	1.28	1.54	2.62	3.74	5.05	6.03
2080	0.48	1.47	1.77	3.21	4.66	6.30	7.58
2090	0.56	1.61	2.00	3.77	5.61	7.67	9.28
2100	0.64	1.74	2.23	4.39	6.69	9.28	11.32

Table 1-D-1: Relative Sea Level Rise Scenario Values for Global Sea Level Rise[1]

Scenarios for SEWELLS POINT
NOAA2017 VLM: 0.00810 feet/yr
All values are expressed in feet

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17	-0.17
2010	-0.09	0.03	0.06	0.13	0.19	0.29	0.29
2020	-0.00	0.26	0.33	0.46	0.62	0.75	0.82
2030	0.08	0.42	0.56	0.82	1.08	1.34	1.47
2040	0.16	0.65	0.82	1.21	1.61	2.06	2.29
2050	0.24	0.85	1.05	1.64	2.23	2.95	3.34
2060	0.32	1.08	1.31	2.13	2.95	3.97	4.62
2070	0.40	1.28	1.54	2.62	3.74	5.05	6.03
2080	0.48	1.47	1.77	3.21	4.66	6.30	7.58
2090	0.56	1.61	2.00	3.77	5.61	7.67	9.28
2100	0.64	1.74	2.23	4.39	6.69	9.28	11.32

[1] USACE's Sea-level Change Curve Calculator (Version 2021.12)

Appendix 1-E: Methodology to Assign Exposure Values to Roadway Segments

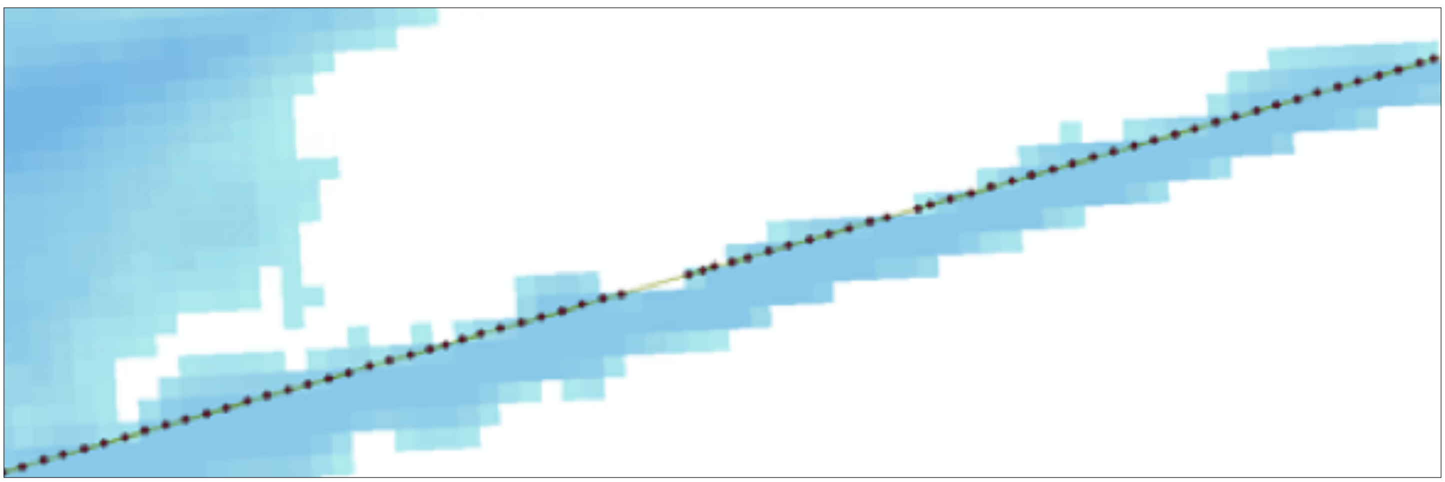
Exposure Assessment Methodology

This appendix outlines the GIS steps performed to assess statewide exposure to sea level rise, storm surge, and inland/riverine flooding for the Commonwealth of Virginia. As noted in Section 1.5, this method does not account for roadway vertical geometry which might be different than ground surface elevations.

- Sea Level Rise
  The following steps were performed to assess the maximum depth of sea level rise experienced by a roadway for a given scenario. Initially the "Zonal Statistics" GIS tool was considered for this analysis, however, it was discovered that this tool had limitations for processing overlapping lines or "zones" resulting in missing values. The following approach was used as an alternate:

1. Conversion of sea level raster data to vector data
2. Intersection of roadway network (VDOT LRS 19.1) with sea level rise vector data to capture only the roadways exposed
3. Develop nodes along the exposed roadways at 1 meter internal (same resolution as raster cells)
4. Sample the sea level rise raster data at each point on roadway network (VDOT LRS 19.1) by extracting values to points (Figure E-1).
5. Summarize the result to obtain the maximum depth for each roadway segment in VDOT LRS 19.1.

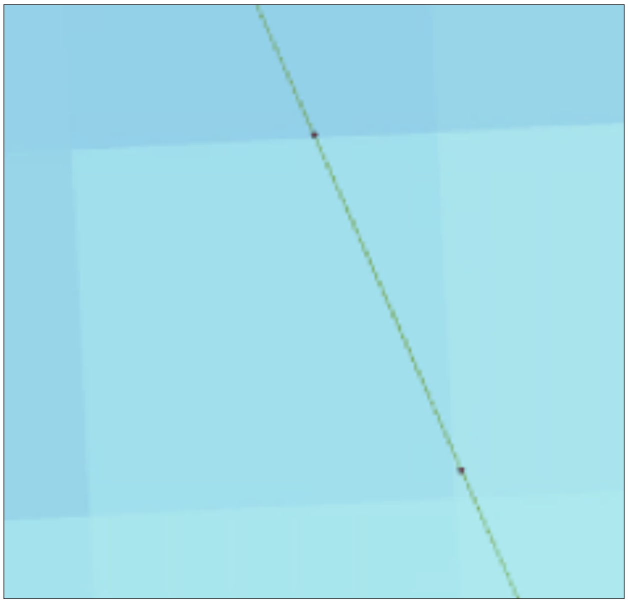
Figure 1-E-1: Sampling of Sea Level Rise Data



- Storm Surge
  The following steps were performed to assess the maximum depth of storm surge experienced by a roadway segment for a given scenario. Initially the "Zonal Statistics" GIS tool was considered for this analysis, however, it was discovered that this tool had limitations for processing overlapping lines or "zones" resulting in missing values. The following approach was used as an alternate:

1. Conversion of storm surge raster data to vector data
2. Intersection of roadway network (VDOT LRS 19.1) with storm surge vector data to capture only the exposed roadway segments.
3. Develop nodes along the exposed roadways at 30 meter internal (same resolution as raster cells)
4. Sample the storm surge raster data at each point on roadway network (VDOT LRS 19.1) by extracting values to points (Figure D-2).
5. Summarize the result to obtain the maximum depth for each roadway segment in VDOT LRS 19.1.

Figure 1-E-2: Sampling of Storm Surge Data



The primary limitation of the method used for assigning storm surge exposure values to roadway segments is that using the same resolution for the line splits as the raster cells leads to the potential of a raster grid cell getting skipped depending on where it is crossed (Figures D-1 and D-2). This could result in a high value raster cell not being reflected in the maximum depth for a given segment, however this issue was not found to be widespread. This error could be reconciled on a subsequent run by shortening the line splits to less than the raster resolution. For example, the sea level rise analysis could be performed with segments of half a meter and the storm surge analysis could be shorted considerably.

This assessment defines exposure to inland/riverine flooding as meeting two conditions:

1. Being within a Location Relative to FEMA Flood Zone or buffer as outlined in Appendix 1-C.

2. Exposed to a historical flood event as outlined in Appendix 1-F.

- Inland/Riverine Flooding (IRF)
  This assessment assigned roadways as being either in or out of the floodplain as well as exposure to a historical weather-related event by means of a direct spatial intersect. Distance of flooded area was not considered at this time. All roadways that touch the floodplain and historical weather-related event buffer were scored a 1 and the rest 0.

Appendix 1-F: Utilizing Historical Weather Events for Inland/Riverine Flooding Exposure and Sensitivity

The data for historic weather events was provided by the VDOT Traffic Operations Division via the VaTraffic (Virginia 511) reporting database. The weather data, including both "Traffic Incidents" and "Road Conditions" were queried from the reporting database by the unique identifier "WX_". All spatial points (latitude/longitude) with prefix "WX" were collected for the time period January 2015 to December 2020.

For the purposes of the VTrans Vulnerability Assessment, only "Traffic Incidents" or "Road Conditions" of the 'Event Type' shown below in Table B-1 were retained for the analysis:

Table 1-F-1: Utilization of the VDOT Historical Weather Event Dataset

Category	Event Types (from data)
Flooding	'flood', 'Flood', 'Flooded', 'Flooding', 'Flooding / High Water'
High Tide	'Heavy fog & High Tide', 'High Tide', 'High tides', 'High Tides', 'Wind and High Tide', 'Wind and High Tides'
High Water	'High water', 'High Water', 'High Wind and Water'
Hurricane	'Coastal Storm', 'Hurricane', 'Hurricane Earl', 'Hurricane Irene'
Mudslide	'Mud', 'Mud in the road.', 'Mud Slide', 'Mudslide'
Washout	'Washout', 'Bridge Washout', 'Road Wash Out', 'Road washed out', 'Road Washed Out', 'Road Washed out/ pipe collapsed', 'Road Washout', 'Roadway is cracked and washing away', 'Roadway washout', 'wash out', 'Wash out', 'Wash Out', 'Washed out', 'Washed Out', 'Washed out bridge', 'washout', 'Washout'
Standing Water	'Standing water', 'Standing Water', 'Standing Water (Ponding)', 'Standing water and trees down'

The weather data described above was formatted a GIS point layer. A 400-foot buffer was developed for each point. Any roadway segments that intersect with any portion of a buffer were considered to be exposed to that historic weather-related event.

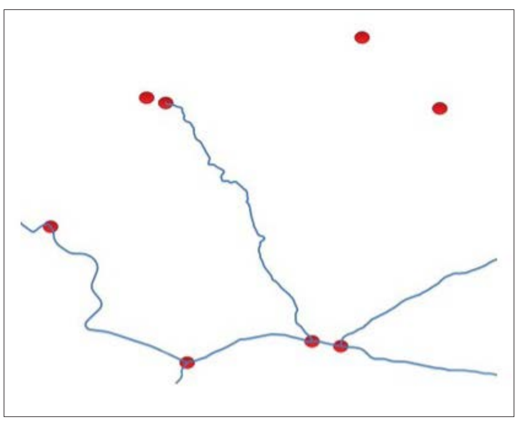


Image 1-F-1: Example of Roadway Segments overlapping with Historical Weather Event Buffers

This layer was also used in the Sensitivity component development. The buffers were merged in order to determine the frequency of weather-related events in a single location, defined as any cluster of overlapping buffers dissolved into one GIS polygon feature. Each polygon was assigned the sum of the overlapping events as the frequency. This frequency was then assigned to the roadway segments that intersected with the merged polygon feature.

Image 1-F-2: Example of Merged Weather Event Buffers Used to Determine Sensitivity

Appendix 1-G: AADT Default Values By Functional Class

The following table shows the default values used to assign to roadway segments for which there is no AADT value assigned, and is developed according to Highway Capacity manual Guidance.[1]

Table 1-G-1: AADT Values by Functional Class

Functional Classification	Assigned Values for Annual Average Daily Traffic (AADT)
Interstate	82,400
Interstate Ramp	16,800
Other Freeways and Expressways	48,600
Other Freeways and Expressways Ramp	16,800
Other Principal Arterial	33,500
Other Principal Arterial Ramp	16,800
Minor Arterial	19,300
Minor Arterial Ramp	16,800
Major Collector	16,800
Major Collector Ramp	16,800
Minor Collector	13,800
Local	5,300
error	5,300
NA	5,300

[1] Transportation Research Board, Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis, 2016.

APPENDIX 2:
VTRANS MACROTREND # 8: GROWTH OF THE PROFESSIONAL SERVICES INDUSTRY
VTRANS MACROTREND # 9: GROWTH OF THE 65+ COHORT
VTRANS MACROTREND # 10: POPULATION AND EMPLOYMENT SHIFT

1. SCOPE OF THIS DEMOGRAPHIC TRENDS ANALYSIS

This technical memorandum identifies historical estimates (from 1975 to 2017) and potential forecasts for population, employment, and household income (for year 2045 from a base year of 2017) from various sources. These socio-demographic variables were deemed important for the development of transportation policies and processes.

1.1 Completeness and Accuracy

Forecasts in general exhibit some uncertainty because they require assumptions about future trends in the economy, in- and outmigration patterns, the environment, or policies that may influence where people choose to live[1]. As information about assumptions is acquired, it is not unusual for forecasts to be updated. Given the uncertainty inherent in such predictions, this memorandum relies on two or more sources to convey the uncertainty and indicates a potential range of values from credible sources. Some of the key factors influencing forecast accuracy are listed below:

- Planning horizon: Longer term forecasts usually have a considerably higher margin of error than shorter term forecasts. Lombard[2] points out that 30-year county-level population projections are expected to have a margin of error of more than 30%; reducing this horizon to 10 years reduces the expected error to 12%. Lombard notes that given an observed 2000 Virginia state-level population of 7.1 million, it is not surprising that a seven year forecast (made in 1993) of 6.9 million was more accurate than a 23 year forecast (made in 1977) of 6.5 million. The more recent forecast took advantage of understanding recent demographic trends.
- Economic trends: Other factors besides transportation investments can affect socioeconomic forecasts. Two such factors are changes in the national economy (where the recessions of 2001 and 2007-2008 appear to have contributed to changes in employment and population growth at the regional level).
- Shift in Population Centers: A shift in Virginia's geographic population center that initially began in the 1970s may cause more uncertainty in the projected populations of the affected cities. During the 1970s, population growth in the Hampton Roads and Richmond areas began to slow while that of Northern Virginia grew.[3] While forecasts show continued population growth therein, the rate of this increase may be difficult to forecast accurately due to the lack of knowledge regarding other factors that may influence this trend.
- External factors: It is not unusual for population estimates to shift. For example, where the Weldon Cooper Center[4] forecast a 2040 Virginia population of 10,201,530, two years later the Weldon Cooper Center[5] forecast a 2040 Virginia population of 9,876,728—a drop of approximately 3.2%. In this instance, "the pace of growth may be a little slower than what was earlier projected,"[2] explaining that at least through year 2030, three factors—fewer people moving to Virginia, a lower birth rate, and more deaths—are expected to yield lower population growth rates than had been observed for the period 2000-2010.
- Size of the units: In some cases size is a good predictor of volatility, where total county population forecasts were more accurate than forecasts of county population by age group. Generally speaking, forecasts for smaller entities tend to have a larger percent error than those of larger entities. For example, as shown in Table 1, the Albemarle County

[1] Sen, S. Population Projections Show that Virginia is Aging and Growing More Slowly, Weldon Cooper Center for Public Service, Charlottesville, 2019. Accessed July 9, 2019.

[2] Lombard, H. How Accurate are Population Projections? Weldon Cooper Center for Public Service, Charlottesville, June 21, 2017. Accessed October 13, 2018.

[3] Sen, S. Despite slowing growth rate, Virginia is projected to be the 10th largest state by 2040. Weldon Cooper Center for Public Service, Charlottesville, June 26, 2017. Accessed November 30, 2018.

[4] Weldon Cooper Center for Public Service. Population Projections by Age and Sex for Virginia and its Localities, 2020-2040. Charlottesville, Virginia, 2017. Accessed October 13, 2018.

[5] Weldon Cooper Center for Public Service. Population Projections for Virginia and its Localities, 2020-2040, Charlottesville, Virginia, 2019. October 13, 2018.

Department of Planning and Community Development's 2010 forecast for five age groups (under 5, 5-19, 20-39, 40-64, and 65+) in 1994 was less accurate than the total population (9%).

- Economic Patterns: Occasionally, unpredictable external factors such as economic patterns will lead to different than expected population growth, and thus greater uncertainty. For example, the City of Williamsburg believes the majority of the 7 percent error in the 1981 forecast can be accounted for by the unanticipated population growth that followed the establishment of Anheuser-Busch Brewery, Busch Gardens, and the Kingsmill development prior to 1981.[1]

Appendix 2 Table 1: Williamsburg Population Forecasts for Year 2000

Year of Comprehensive Plan	2000 Projection	2000 Census	Percent Error
1981	11,200	11,998	-7%
1989	13,522	11,998	13%

Appendix 2 Table 2: Albemarle County Population Forecasts for Year 2010[2]

Jurisdiction (age group)	1990	2010 Forecast	2010 Observed	Percent Error[3]
Albemarle County (0-4)	4,655	4,858	5,527	12%
Albemarle County (5-19)	14,670	18,704	21,032	11%
Albemarle County (20-39)	24,807	25,706	25,062	-3%
Albemarle County (40-64)	17,310	28,876	33,225	13%
Albemarle County (age 65+)	6,598	12,004	14,124	15%
Albemarle County (all ages)	68,040[4]	90,148	98,970	9%
Charlottesville City (all ages)	40,341	41,225	43,475	5%
Virginia (all ages)	6,187,358	7,451,158	8,001,024	7%

- Size of the jurisdiction: Using the same source as above,[5] the population forecast error for Albemarle County (9%) was about twice as large as that of the City of Charlottesville (5%). In this case, a contributing factor may have been that the City of Charlottesville was relatively stable. For the period from 1990-2010, Charlottesville's population was forecast to grow only by 2%; by contrast, Albemarle County's population was forecast to grow by 32%.
- Forecasting techniques: A Metropolitan Washington Council of Governments (MWCOG) document associated with the earlier (Round 7) forecasts for year 2030[6] points out that these forecasts are based on a cooperative process that aligns regional level forecasts with local forecasts (which incorporate planned projects) developed by each jurisdiction, a subcommittee comprised of representatives from these jurisdictions as well as MWCOG staff work to "reconcile" these local and regional projections. Similarly, the Weldon Cooper Center for Public Service[7] uses several data inputs but not such local plans. Table 3 shows a comparison of these forecasts.

[1] City of Williamsburg Planning Department. Williamsburg Comprehensive Plan: Appendix A1 – Past Comprehensive Plans, 2013. Accessed December 11, 2018.

[2] Note: Forecasts based on Albemarle County Department of Planning and Community Development (1994) and observed values based on Albemarle County Department of Community Development (2011).

[3] Note: Percent error is computed as (forecast value – observed value) /observed value.

[4] Note: The reported value is 68,040, however, the total of these age groups is 68,172.

[5] Albemarle County Department of Planning and Community Development. Albemarle County Information Sheet, Charlottesville, 1994.

[6] Metropolitan Washington Council of Governments. Final Round 9.1 Cooperative Forecasts. Washington, DC, 2018. Accessed December 6, 2018.

[7] Weldon Cooper Center for Public Service. Virginia Population Projections Methodology. Charlottesville, Virginia, 2019c. Accessed January 29, 2020.

Appendix 2 Table 3: Comparison of MWCOG (2018) and Weldon Cooper (2017a) Population Projections for 2045[1]

Jurisdiction	MWCOG (thousands)	Weldon Cooper (thousands)	Percent Difference[2]
Arlington County	301.2	325.1	7.36%
City of Alexandria	208.5	223.2	6.62%
Fairfax County	1,416.80.0	1,386.4	-2.19%
City of Fairfax	35.2	25.5	-37.59%
City of Falls Church	17.6	21.6	18.63%
Loudoun County	507.4	755.8	32.87%
Prince William County	584.0	729.1	19.91%
City of Manassas	52.1	53.9	3.43%
City of Manassas Park	15.9	25.2	36.92%
King George County	47.0	37.1	-26.40%
Spotsylvania County	253.6	192.5	-31.74%
Stafford County	267.9	222.5	-20.38%
City of Fredericksburg	36.2	40.9	11.59%
Total	3,743.4	4,039.4	7.33%

2. METHODOLOGY

The primary methods used for the purposes of this technical memorandum include:

- Data Collection: Collect estimates and forecast data for population, employment, and household income at the county level;
- Data Aggregation: Develop population, employment, and household income estimates and forecasts for Virginia Department of Transportation (VDOT) Construction Districts (Figure 1) and Modified Planning District Commissions (PDC) (Figure 2). See Appendix 2-B for methodology for determining modified PDC areas.

Figure 1: Virginia Department of Transportation Construction Districts

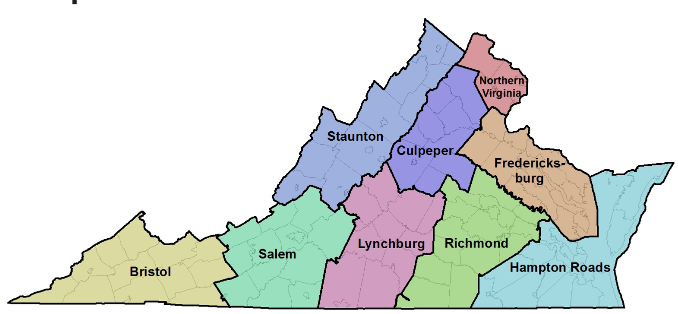
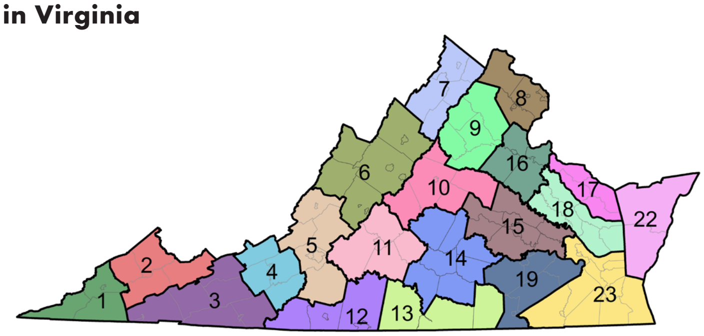


Figure 2: Modified Planning District Commissions in Virginia



1 Lenowisco
2 Cumberland Plateau
3 Mount Rogers
4 New River Valley
5 Roanoke Valley-Alleghany
6 Central Shenandoah
7 Northern Shenandoah
8 Northern Virginia
9 Rappahannock-Rapidan
10 Thomas Jefferson
11 Region 2000 Local Government Council
12 West Piedmont
13 Southside
14 Commonwealth Regional Council
15 Richmond Regional
16 George Washington
17 Northern Neck
18 Middle Peninsula
19 Crater
20 Accomack-Northampton
21 Hampton Roads

[1] Forecasts based on data in Metropolitan Washington Council of Governments (MWCOG) Final Round 9.1 Cooperative Forecasts (2018) and Weldon Cooper Center for Public Service (2017a)

[2] Percent error is computed as 100* (WC projection value – MWCOG projection value/WC projection value).

2.1. Data Collection

Table 4 lists planning horizon years and data sources that were used for this analysis.

Appendix 2 Table 4: Planning Horizons and Data Sources

	Source	Historic Year(s)	Base Year	Forecast Year
Population	Weldon Cooper Center for Public Service	1975 - 2017	2017	2045
	Woods & Poole Economics, Inc. (Woods & Poole)	2000	2017	2045
Employment	*Bureau of Labor Statistics*	*1975-2017*	-	-
	Woods & Poole	2000	2017	2045
	IHS Markit	2000	2017	2045
Household Income	Woods & Poole	2000	2017	2045
	Moody's Analytics	2000	2017	2045

2.2. Data Aggregation

Data was collected for each independent city and county in Virginia and aggregated by the VDOT Construction District and Modified Planning District Commission (PDC). For more information, see Appendix 2-A: Jurisdictions Associated with Each VDOT Construction District and Appendix 2-B: Jurisdictions Associated with each Modified Planning District Commission.

For each VDOT Construction District and PDC the change in population, employment and household income between base year and forecast year were calculated on both a nominal and a percentage basis. This processing required some data adjustments, as detailed in Appendix 2-C: Development of Population, Employment, and Household Income Estimates and Projections.

3. RESULTS

The following results include major demographic variables of interest: population; employment; and household income.

3.1. Historical Population

Table 5 includes population by VDOT Construction District and Modified Planning District Commission from 1975 to 2017.

Appendix 2 Table 5: Base and Historical Year Population (1975-2017)[1]

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2017
STATEWIDE										
Total	5,056,000	5,346,818	5,715,200	6,187,358	6,696,000	7,079,030	7,600,467	8,001,024	8,382,993	8,470,020
VDOT CONSTRUCTION DISTRICTS										
Bristol	361,000	387,056	378,800	360,041	365,700	363,236	359,956	364,661	356,897	348,862
Culpeper	206,800	224,290	240,600	267,956	295,000	319,988	357,149	385,746	404,735	412,685
Fredericksburg	191,600	219,611	242,500	287,606	336,700	374,081	437,616	469,028	492,144	501,541
Hampton Roads	1,226,800	1,266,402	1,366,600	1,491,759	1,575,000	1,621,695	1,678,923	1,705,262	1,764,170	1,766,213
Lynchburg	356,300	363,299	361,400	361,722	375,900	380,728	384,517	398,710	401,945	399,270
Northern Virginia	1,019,200	1,105,714	1,287,500	1,466,409	1,649,300	1,815,197	2,055,150	2,230,623	2,436,146	2,491,299
Richmond	794,600	841,582	879,400	946,067	1,025,700	1,087,582	1,162,116	1,230,462	1,282,919	1,300,765
Salem	546,600	569,586	580,600	596,688	628,600	648,960	663,437	685,388	695,583	694,336
Staunton	353,100	369,278	377,800	409,110	444,100	467,563	501,603	531,144	548,454	555,049

[1] Aggregated from figures reported by the Weldon Cooper Center for Public Service (undated, 1993, 2003, 2011, 2019a)

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2017
MODIFIED PLANNING DISTRICT COMMISSIONS										
Accomack-Northampton	46,000	45,893	44,800	44,764	48,400	51,398	48,263	45,553	45,692	45,041
Central Shenandoah	203,000	208,344	211,700	225,025	244,900	258,763	271,162	286,781	297,621	300,228
Central Virginia	184,300	194,178	198,900	206,226	220,500	228,616	237,660	252,634	259,900	261,208
Commonwealth Regional Council	82,400	83,549	84,100	84,905	91,900	97,102	100,148	104,609	104,667	103,451
Crater	161,100	161,959	158,600	156,457	162,300	167,129	168,866	173,463	174,732	173,056
Cumberland Plateau	126,900	140,067	135,400	123,580	122,900	117,229	113,726	113,976	110,381	106,569
George Washington	96,800	118,674	133,900	170,410	208,900	241,044	301,102	327,773	350,535	360,264
Hampton Roads	1,147,500	1,187,846	1,290,300	1,416,443	1,493,100	1,533,739	1,594,054	1,622,394	1,681,880	1,685,483
Lenowisco	94,300	99,644	97,900	91,520	92,300	93,105	93,056	94,174	91,830	89,755
Middle Peninsula	55,300	59,987	66,900	73,023	79,700	83,684	86,823	90,826	91,248	91,199
Mount Rogers	172,400	181,139	179,400	178,205	186,000	188,984	189,661	193,595	191,012	188,498
New River Valley	132,700	141,343	146,000	152,720	158,700	165,146	171,043	178,237	182,991	183,054
Northern Neck	39,500	40,950	41,700	44,173	48,100	49,353	49,690	50,429	50,361	50,078
Northern Shenandoah	122,700	132,492	139,700	159,239	174,800	185,282	207,791	222,152	229,120	233,566
Northern Virginia	1,019,200	1,105,714	1,287,500	1,466,409	1,649,300	1,815,197	2,055,150	2,230,623	2,436,146	2,491,299
Rappahannock-Rapidan	83,300	92,897	100,700	116,524	125,700	134,785	153,839	166,054	171,228	174,369
Richmond Regional	585,700	632,015	671,700	739,735	811,600	865,941	938,519	1,002,696	1,054,636	1,074,374
Roanoke Valley-Alleghany	280,800	288,523	289,600	293,244	306,100	311,827	319,760	330,918	335,658	335,483
Southside	83,700	82,768	82,000	81,258	85,600	88,149	87,273	86,402	84,304	83,060
Thomas Jefferson	135,600	143,597	152,400	164,210	182,700	199,648	217,980	234,712	248,500	253,174
West Piedmont	202,800	205,239	202,000	199,288	202,500	202,909	194,900	193,023	190,545	186,811

Notes: Cell shading indicates relative comparative values.

3.2. Population Forecasts

Table 6 includes the forecast population change by VDOT Construction District and Modified Planning District Commission from 2017 to 2045.

Appendix 2 Table 6: Forecast Population (2017-2045)[1]

	Historic and Base Year Population		Forecast Population		Statewide Population Share				Change (2017-2045)	
	2000	2017	2045 (WC)	2045 (WP)	2000	2017	2045 (WC)	2045 (WP)	WC	WP
STATEWIDE										
Total	7,079,030	8,470,020	10,528,817	11,283,149	-	-	-	-	24%	33%
VDOT CONSTRUCTION DISTRICTS										
Bristol	363,236	345,314	325,987	364,412	5%	4%	3%	3%	-6%	6%
Culpeper	319,988	415,063	543,665	558,203	5%	5%	5%	5%	31%	35%
Fredericksburg	374,081	506,111	685,611	777,815	5%	6%	7%	7%	36%	54%
Hampton Roads	1,621,695	1,746,491	1,980,157	2,033,689	23%	21%	19%	18%	13%	16%
Lynchburg	380,728	396,872	423,421	425,827	5%	5%	4%	4%	7%	7%
Northern Virginia	1,815,197	2,501,308	3,546,256	3,870,499	26%	30%	34%	34%	42%	55%
Richmond	1,087,582	1,310,261	1,596,976	1,732,422	15%	15%	15%	15%	22%	32%
Salem	642,661	693,462	752,932	822,009	9%	8%	7%	7%	9%	19%
Staunton	467,563	555,138	673,812	698,273	7%	7%	6%	6%	21%	26%
MODIFIED PLANNING DISTRICT COMMISSIONS										
Accomack-Northampton	51,398	44,391	34,765	45,700	1%	1%	0%	0%	-22%	3%
Central Shenandoah	258,763	299,042	358,808	372,547	4%	4%	3%	3%	20%	25%
Central Virginia	222,317	261,254	306,881	325,873	3%	3%	3%	3%	18%	25%
Commonwealth Regional Council	97,102	102,387	112,874	111,130	1%	1%	1%	1%	10%	9%
Crater	167,129	173,092	181,355	174,268	2%	2%	2%	2%	5%	1%
Cumberland Plateau	117,229	104,439	90,196	108,534	2%	1%	1%	1%	-14%	4%
George Washington	241,044	364,840	535,363	613,297	3%	4%	5%	5%	47%	68%
Hampton Roads	1,533,739	1,667,226	1,910,793	1,953,027	22%	20%	18%	17%	15%	17%
Lenowisco	93,105	88,145	87,537	93,049	1%	1%	1%	1%	-1%	6%
Middle Peninsula	83,684	91,489	100,294	109,228	1%	1%	1%	1%	10%	19%
Mount Rogers	188,984	189,063	182,897	204,837	3%	2%	2%	2%	-3%	8%
New River Valley	165,146	182,993	208,993	202,913	2%	2%	2%	2%	14%	11%
Northern Neck	49,353	49,782	49,953	55,290	1%	1%	0%	0%	0%	11%
Northern Shenandoah	185,282	235,443	297,472	307,533	3%	3%	3%	3%	26%	31%
Northern Virginia	1,815,197	2,501,308	3,546,256	3,870,499	26%	30%	34%	34%	42%	55%
Rappahannock-Rapidan	134,785	177,418	228,219	251,646	2%	2%	2%	2%	29%	42%
Richmond Regional	865,941	1,084,424	1,366,353	1,503,263	12%	13%	13%	13%	26%	39%
Roanoke Valley-Alleghany	311,827	334,781	365,274	386,317	4%	4%	3%	3%	9%	15%
Southside	88,149	81,493	72,959	78,681	1%	1%	1%	1%	-11%	-4%
Thomas Jefferson	199,648	252,588	330,711	323,373	3%	3%	3%	3%	31%	28%
West Piedmont	202,909	184,422	160,864	192,144	3%	2%	2%	2%	-13%	4%

Notes: Cell shading indicates relative comparative values.

[1] WC - Aggregated from data provided by Weldon Cooper Center for Public Service. WP - Aggregated from data provided by Woods & Poole (2018b)

Appendix 2 Table 7: Relative Population Distribution in Virginia by Age Group[1]

Age Group	2000	2017	2040	2045
Under 20	27%	25%	25%	24%
20-64	62%	60%	56%	56%
65+	11%	15%	19%	20%
75+	5%	6%	10%	11%

Appendix 2 Table 8: Forecast Population over Age 65 in Virginia

	Base Year (2017) Population			Change Age 65 + (2017-2045)	
	Total	Age 65 +	Share of Age 65+	WC	WP
STATEWIDE					
Total	8,470,020	1,271,428	15%	*56%*	*78%*
VDOT CONSTRUCTION DISTRICTS					
Bristol	345,314	73,301	21%	*10%*	*35%*
Culpeper	415,063	70,998	17%	*30%*	*49%*
Fredericksburg	506,111	78,451	16%	*20%*	*18%*
Hampton Roads	1,746,491	250,597	14%	*53%*	*76%*
Lynchburg	396,872	77,687	20%	*53%*	*66%*
Northern Virginia	2,501,308	282,142	11%	*71%*	*100%*
Richmond	1,310,261	202,690	15%	*64%*	*73%*
Salem	693,462	134,105	19%	*45%*	*63%*
Staunton	555,138	101,457	18%	*92%*	*132%*
MODIFIED PLANNING DISTRICT COMMISSIONS					
Accomack-Northampton	44,391	10,448	24%	10%	33%
Central Shenandoah	*299,042*	*54,481*	*18%*	*1%*	*40%*
Central Virginia	*261,254*	*48,177*	*18%*	*17%*	*32%*
Commonwealth Regional Council	*102,387*	*19,712*	*19%*	*32%*	*37%*
Crater	*173,092*	*28,370*	*16%*	*27%*	*44%*
Cumberland Plateau	*104,439*	*22,362*	*21%*	*40%*	*65%*
George Washington	*364,840*	*44,326*	*12%*	*55%*	*67%*
Hampton Roads	*1,667,226*	*234,046*	*14%*	*92%*	*132%*
Lenowisco	*88,145*	*17,511*	*20%*	*64%*	*94%*
Middle Peninsula	*91,489*	*19,541*	*21%*	*58%*	*53%*
Mount Rogers	*189,063*	*41,881*	*22%*	*36%*	*45%*
New River Valley	*182,993*	*28,400*	*16%*	*10%*	*26%*
Northern Neck	*49,782*	*14,584*	*29%*	*5%*	*17%*
Northern Shenandoah	*235,443*	*42,127*	*18%*	*34%*	*22%*
Northern Virginia	*2,501,308*	*282,142*	*11%*	*59%*	*90%*
Rappahannock-Rapidan	*177,418*	*31,081*	*18%*	*111%*	*163%*
Richmond Regional	*1,084,424*	*161,285*	*15%*	*2%*	*-5%*
Roanoke Valley-Alleghany	*334,781*	*66,761*	*20%*	*31%*	*35%*
Southside	*81,493*	*19,295*	*24%*	*40%*	*26%*
Thomas Jefferson	*252,588*	*43,860*	*17%*	*-3%*	*8%*
West Piedmont	*184,422*	*41,038*	*22%*	*56%*	*70%*

Notes: Cell shading indicates relative comparative values

[1] Based on data from Woods & Poole (2018b) and data from the Weldon Cooper Center for Public Service and the U.S. Census Bureau (2018a).

3.3. Historical Employment

Table 8 includes the historical employment by VDOT Construction District and Modified Planning District Commission based on the Bureau of Labor Statistics.

Appendix 2 Table 9: Employment in Virginia (1975-2017)[1]

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2017
STATEWIDE										
Total	1,472,963	2,028,943	2,331,590	2,760,330	2,938,352	3,353,730	3,517,894	3,470,218	3,645,346	3,727,418
Percent Missing	4.1%	2.3%	2.4%	2.4%	2.3%	2.1%	1.7%	1.9%	2.4%	2.9%
VDOT CONSTRUCTION DISTRICTS										
Bristol	79,297	108,464	106,612	117,430	124,085	125,571	126,738	123,847	116,696	114,088
Culpeper	54,226	78,836	87,884	107,118	114,377	132,158	144,906	145,679	159,612	165,542
Fredericksburg	26,947	54,448	64,067	82,421	97,166	120,592	138,593	142,413	151,326	157,169
Hampton Roads	343,610	459,889	536,886	615,454	645,320	719,156	754,134	727,600	751,128	763,215
Lynchburg	103,824	133,494	134,535	145,334	153,235	164,474	154,995	146,707	150,836	152,028
Northern Virginia	289,711	446,235	597,681	759,924	819,531	1,008,277	1,101,677	1,127,234	1,187,488	1,221,898
Richmond	305,016	391,106	421,701	496,556	520,715	578,460	594,115	578,090	626,559	644,602
Salem	167,444	217,852	238,812	267,220	280,606	295,040	284,596	269,676	280,786	281,287
Staunton	102,888	138,619	143,412	168,873	183,317	210,002	218,140	208,972	220,915	227,589
MODIFIED PLANNING DISTRICT COMMISSIONS										
Accomack-Northampton	10,236	14,869	15,457	17,334	17,920	19,285	19,064	18,471	18,195	18,125
Central Shenandoah	60,062	80,621	82,182	97,650	104,969	119,258	122,688	118,575	124,153	127,705
Central Virginia	55,585	77,470	79,991	91,470	95,541	102,959	98,908	97,124	98,464	99,144
Commonwealth Regional Council	15,746	20,479	21,017	24,206	25,310	27,410	27,846	26,011	26,854	27,387
Crater	43,683	55,778	53,455	60,401	63,312	68,556	67,844	67,114	69,329	69,113
Cumberland Plateau	27,253	37,701	34,349	35,931	35,766	35,602	35,654	35,489	32,860	31,578
George Washington	12,777	30,369	38,034	52,605	63,837	84,835	100,510	105,939	115,812	120,770
Hampton Roads	326,753	434,918	510,959	585,885	614,025	685,366	721,221	695,099	718,837	731,066
Lenowisco	16,290	23,585	23,593	25,250	26,632	26,523	28,319	29,751	25,212	24,115
Middle Peninsula	8,439	13,472	15,263	17,831	20,816	22,389	24,088	22,352	22,475	23,085
Mount Rogers	45,272	59,344	60,891	70,718	77,207	79,012	76,792	71,014	71,172	70,983
New River Valley	37,465	49,393	54,027	58,950	60,938	67,541	67,767	63,786	69,153	69,250
Northern Neck	5,731	10,607	10,770	11,985	12,513	13,368	13,995	14,122	13,039	13,314
Northern Shenandoah	35,659	48,604	52,155	63,084	69,595	81,945	86,110	82,409	88,862	92,054
Northern Virginia	289,711	446,235	597,681	759,924	819,531	1,008,277	1,101,677	1,127,234	1,187,488	1,221,898
Rappahannock-Rapidan	15,114	24,090	27,252	33,919	36,623	42,580	50,009	47,758	50,870	52,337
Richmond Regional	248,638	321,067	353,802	419,918	441,914	493,421	510,829	498,310	544,925	563,510

[1] Aggregated from figures reported by the Bureau of Labor Statistics (2018b)

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2017
Roanoke Valley-Alleghany	91,500	114,767	127,360	141,926	154,015	163,087	160,036	152,774	158,330	158,688
Southside	20,658	26,475	26,741	26,135	29,327	33,449	30,592	28,720	27,846	27,434
Thomas Jefferson	40,067	56,827	63,047	75,959	80,735	92,974	98,377	101,322	113,021	117,146
West Piedmont	66,324	82,272	83,564	89,249	87,826	85,893	75,568	66,844	68,449	68,716

Notes: Cell shading indicates relative comparative values.

3.4. Employment Forecasts

Table 9 includes the forecast employment change and forecast share of statewide employment by VDOT Construction District and Modified Planning District Commission from 2017 to 2045.

Appendix 2 Table 10: Forecast Employment (2017-2045)[1]

	Base Year		Forecast		Statewide Share				Change (2017-2045)	
	2017 (IHS)	2017 (WP)	2045 (IHS)	2045 (WP)	2017 (IHS)	2017 (WP)	2045 (IHS)	2045 (WP)	IHS	WP
STATEWIDE										
Total	4,017,630	5,275,247	4,750,031	7,601,370	-	-	-	-	18%	44%
VDOT CONSTRUCTION DISTRICTS										
Bristol	137,963	*160,837*	133,790	*190,791*	*3%*	*3%*	*3%*	*3%*	-3%	*19%*
Culpeper	182,501	*245,104*	223,952	*340,085*	*5%*	*5%*	*5%*	*4%*	23%	*39%*
Fredericksburg	167,649	*229,539*	206,660	*360,323*	*4%*	*4%*	*4%*	*5%*	23%	*57%*
Hampton Roads	820,225	*1,084,989*	906,968	*1,449,070*	*21%*	*20%*	*19%*	*19%*	11%	*34%*
Lynchburg	169,564	*211,032*	175,139	*277,339*	*4%*	*4%*	*4%*	*4%*	3%	*31%*
Northern Virginia	1,293,486	*1,756,035*	1,690,425	*2,746,961*	*32%*	*33%*	*36%*	*36%*	31%	*56%*
Richmond	690,926	*878,820*	812,072	*1,289,150*	*17%*	*17%*	*17%*	*17%*	18%	*47%*
Salem	309,107	*390,909*	329,935	*512,624*	*8%*	*7%*	*7%*	*7%*	7%	*31%*
Staunton	246,209	*317,982*	271,090	*435,027*	*6%*	*6%*	*6%*	*6%*	10%	*37%*
MODIFIED PLANNING DISTRICT COMMISSIONS										
Accomack-Northampton	22,934	25,877	17,023	32,932	1%	0%	1%	0%	-26%	27%
Central Shenandoah	136,473	177,971	149,465	243,015	3%	3%	3%	3%	10%	37%
Central Virginia	108,254	140,329	116,201	197,168	3%	3%	2%	3%	7%	41%
Commonwealth Regional Council	33,539	41,709	32,476	51,888	1%	1%	1%	1%	-3%	24%
Crater	75,717	98,383	94,824	114,439	2%	2%	2%	2%	25%	16%
Cumberland Plateau	37,344	43,153	31,598	51,344	1%	1%	1%	1%	-15%	19%
George Washington	126,033	170,468	165,370	285,512	3%	3%	3%	4%	31%	68%
Hampton Roads	782,271	1,041,008	873,686	1,394,797	19%	20%	18%	18%	12%	34%
Lenowisco	30,099	34,745	30,691	42,769	1%	1%	1%	1%	2%	23%
Middle Peninsula	25,641	36,740	26,564	46,823	1%	1%	1%	1%	4%	27%
Mount Rogers	83,033	100,303	87,584	119,503	2%	2%	2%	2%	6%	19%
New River Valley	81,129	96,630	89,105	121,907	2%	2%	2%	2%	10%	26%
Northern Neck	15,975	22,331	14,726	27,988	0%	0%	0%	0%	-8%	25%
Northern Shenandoah	101,843	129,823	111,115	180,494	3%	2%	2%	2%	9%	39%

[1] IHS - Aggregated from data provided by IHS Markit (Jeafarqomi, 2018). WP - Aggregated from data provided by Woods & Poole (2018)

	Base Year		Forecast		Statewide Share				Change (2017-2045)	
	2017 (IHS)	2017 (WP)	2045 (IHS)	2045 (WP)	2017 (IHS)	2017 (WP)	2045 (IHS)	2045 (WP)	IHS	WP
Northern Virginia	1,293,486	1,756,035	1,690,425	2,746,961	32%	33%	36%	36%	31%	56%
Rappahannock-Rapidan	61,922	86,185	69,782	126,907	2%	2%	1%	2%	13%	47%
Richmond Regional	598,022	759,909	706,346	1,150,963	15%	14%	15%	15%	18%	52%
Roanoke Valley-Alleghany	169,783	214,525	173,240	280,520	4%	4%	4%	4%	2%	31%
Southside	32,858	39,058	26,725	46,396	1%	1%	1%	1%	-19%	19%
Thomas Jefferson	125,463	166,318	158,984	222,628	3%	3%	3%	3%	27%	34%
West Piedmont	75,811	93,747	84,101	116,416	2%	2%	2%	2%	11%	24%

Notes: Cell shading indicates relative comparative values.

3.5. Historical and Forecast Household Income

Table 10 includes the historical and forecast household income by VDOT Construction District and Modified Planning District Commission from 2000 to 2045 based on two distinct sources[1], Woods & Poole (Weighted Mean Household Income) and Moody's Analytics (Weighted Median Household Income).

Appendix 2 Table 11: Weighted Household Income (in 2009 dollars)[2]

	Household Income (Median)				Household Income (Mean)			
	2000	2017	2045	Change (2017-2045)	2000	2017	2045	Change (2017-2045)
STATEWIDE								
Total	$61,502	$68,351	$85,741	25%	$100,897	$120,910	$166,467	38%
VDOT CONSTRUCTION DISTRICTS								
Bristol	$33,247	$33,923	$43,039	27%	$59,247	$67,950	*$91,147*	*34%*
Culpeper	$57,700	$64,524	$84,411	31%	$99,285	$121,092	*$155,098*	*28%*
Fredericksburg	$62,479	$70,703	$90,336	28%	$90,439	$113,106	*$152,346*	*35%*
Hampton Roads	$52,610	$56,719	$68,287	20%	$87,128	$106,960	*$146,272*	*37%*
Lynchburg	$40,017	$37,297	$48,518	30%	$65,868	$73,571	*$102,413*	*39%*
Northern Virginia	$93,690	$104,225	$124,142	19%	$153,295	$172,388	*$227,461*	*32%*
Richmond	$56,646	$59,469	$72,087	21%	$95,393	$113,744	*$156,125*	*37%*
Salem	$44,073	$46,261	$57,443	24%	$71,712	$82,339	*$109,938*	*34%*
Staunton	$48,042	$50,053	$67,381	35%	$75,443	$90,182	*$117,615*	*30%*
MODIFIED PLANNING DISTRICT COMMISSIONS								
Accomack-Northampton	$35,900	$36,220	$52,930	46%	$60,596	$80,544	$111,527	38%
Central Shenandoah	$46,135	$44,286	$59,988	35%	$72,376	$84,524	$107,818	28%
Central Virginia	$45,863	$43,515	$53,778	24%	$75,293	$80,534	$109,342	36%

[1] Woods & Poole (2018a) reports the *mean* household income, whereas Moody's (2019) reports the *median* household income. In locations where there were some households with very large or very small household incomes, there could be a difference between the mean and the median incomes. Further, Moody's (2019) and Woods & Poole (2018a, 2018b) do not define income in the same manner. While both sources include wages and salaries, Woods & Poole also includes "proprietors' income, rental income of persons, dividend income, personal interest income, and transfer payments less personal contributions for social insurance." While Moody's income includes transfer payments (e.g., social security income and public assistance income [Moody's, 2019; U.S. Census Bureau, 2018c]), Woods & Poole (2018b) notes that income as reported by the U.S. Census Bureau excludes certain items such as the value of food stamps, medical payments, the rental value of one's residence.

[2] Calculated based on data provided by Woods & Poole (2018). Incomes are in year 2009 dollars.

	Household Income (Median)				Household Income (Mean)			
	2000	2017	2045	Change (2017-2045)	2000	2017	2045	Change (2017-2045)
Commonwealth Regional Council	$37,658	$38,382	$51,926	35%	$60,624	$69,800	$92,374	32%
Crater	$45,244	$52,116	$57,065	9%	$73,345	$84,047	$113,054	35%
Cumberland Plateau	$30,220	$31,986	$39,061	22%	$58,806	$63,893	$86,968	36%
George Washington	$71,355	$80,235	$98,644	23%	$98,370	$123,298	$164,866	34%
Hampton Roads	$53,504	$57,641	$68,900	20%	$88,679	$108,505	$148,086	36%
Lenowisco	$30,386	$30,356	$40,856	35%	$53,519	$60,582	$82,469	36%
Middle Peninsula	$51,905	$53,696	$67,646	26%	$81,274	$95,167	$118,114	24%
Mount Rogers	$36,918	$36,139	$46,380	28%	$62,245	$73,164	$96,054	31%
New River Valley	$39,849	$46,208	$54,105	17%	$60,927	$74,194	$98,370	33%
Northern Neck	$42,508	$44,327	$66,535	50%	$72,252	$84,637	$109,504	29%
Northern Shenandoah	$51,470	$58,491	$77,388	32%	$80,905	$98,865	$130,661	32%
Northern Virginia	$93,690	$104,225	$124,142	19%	$153,295	$172,388	$227,461	32%
Rappahannock-Rapidan	$62,668	$68,849	$85,352	24%	$104,357	$119,278	$154,414	29%
Richmond Regional	$59,927	$61,807	$74,893	21%	$101,449	$120,482	$163,575	36%
Roanoke Valley-Alleghany	$47,633	$48,139	$57,262	19%	$78,026	$90,024	$123,882	38%
Southside	$36,656	$36,607	$51,905	42%	$59,716	$69,878	$97,414	39%
Thomas Jefferson	$53,514	$60,642	$82,982	37%	$94,282	$120,204	$153,176	27%
West Piedmont	$37,286	$34,612	$50,430	46%	$62,940	$70,094	$91,768	31%

Notes: Cell shading indicates relative comparative values.

4. SUMMARY OF FINDINGS

4.1. Population Forecast

1. Population Growth: Virginia's population is forecast to grow between 24% and 33% between 2017 and 2045. On an annual basis, this forecast growth rate of (0.78% -1.03%) is near the upper middle of the forecast growth rates of border states, surpassed by North Carolina (1.18%), inclusive of Tennessee (0.98%), and larger than the forecast rates of West Virginia (<0.01%), Kentucky (0.40%), and Maryland (0.57%).
2. Population Growth rates: Population growth rates have decreased since 2000, with 1975-2000 showing greater average annual growth rates for most (8 of 9) Construction Districts than 2000-2017. Results show a greater average annual increase during 1975-2000 in all but Lynchburg Construction District.
3. Population growth in Virginia's urban crescent: Virginia's current population is unevenly distributed by jurisdictions, and by VDOT Construction District. Virginia's Urban Crescent is roughly defined as one connecting three urbanized areas in Virginia: Hampton Roads, Richmond, and Northern Virginia. Three of Virginia's Construction Districts account for almost two-thirds (63%) of Virginia's 2017 population, and 10 of Virginia's 133 cities and counties account for almost half (48%) of the Commonwealth's 2017 population. Northern Virginia had the second largest relative increase in population from 1975 to 2017, behind Fredericksburg, with the latter's 2017 population being 2.44 times that of 1975. Bristol was the only Construction District to show a decrease in population from 1975 to 2017, where the 2017 population was a 3.4% drop compared to its 1975 population (i.e. its ratio of 2017/1975 was 0.966).
    a. Population growth in Four PDCs: Four of Virginia's 21 PDCs, clustered along the I-95 corridor (Northern Virginia, George Washington, and Richmond Regional) and the eastern portion of the I-64 corridor (Hampton Roads PDC) are expected to account for 83%-85% of this growth.
    b. Population decline in Four PDCs: For one data source, four PDCs (Cumberland Plateau, Southside, West Piedmont, and Accomack-Northampton) are forecast to have double-digit population declines of 10% to 22% between 2017 and 2045; for another data source, just one of these PDCs (Southside) will see a decline (of about 4%).
    c. Growth in Northern Virginia: The Northern Virginia Construction District is accounting for an increasing percentage of Virginia's total population. The Northern Virginia area has continued to grow in size since the 1970s, which has resulted in Virginia's center of population shifting north. With the growth of Northern Virginia's population being much greater than the decline in population of other area, Virginia's population has increased 68% from 1975 to 2017. Northern Virginia's increase in population by 144% from 1975 to 2017 was a much greater increase than that of Virginia's statewide population. Though other Construction Districts continue to increase in population, the VDOT Northern Virginia Construction District went from 20.2% of the Commonwealth's population in 1975 to 29.4% in 2017.
4. Aging Population: Virginia's population age 65+ is forecast to increase from 1.27 million to between 1.99 million and 2.26 million between 2017 and 2045. Much of this increase is expected to occur in Construction Districts that presently have comparatively lower proportions of persons age 65+, such as Northern Virginia.
    a. 75+ cohort: Although persons age 75+ are a relatively small percentage of the state's population at present (6%), this group is expected to grow by 104%-150%, becoming between 10% and 11% of the total state's population. A doubling (e.g., 100% increase or more) of this age cohort is expected in several Construction Districts, including some urban ones that presently have comparatively lower percentages of persons age 75+.

4.2. Employment Forecast

1. Employment growth: Virginia's employment is forecast to grow between 18.2% and 44.1% between 2017 and 2045. On an annual basis, this range of forecast growth rates (0.60% -1.31%) encompasses the forecast growth rates for the District of Columbia (0.76%-0.82%), Maryland (1.28%), and North Carolina (1.29%) and is surpassed by the forecast growth rate for Tennessee (1.46%).
    a. Growth rates: Fredericksburg (57%), Northern Virginia (56%) and Richmond (47%) are expected to exceed the statewide average employment growth (44%).
    b. Slowing employment growth: The employment growth rate has slowed. Using the year 2000 as a demarcation, Virginia's average annual employment growth rate slowed from 3.3% (1975-2000) to 0.62% (2000-2017). For 1975-1980, 1980-1985, and 1985-1990, statewide total employment showed annual growth rates of 6.2%, 2.8%, and 3.4%, respectively; for the periods 2005-2010, 2010-2015, and 2015-2017 these growth rates were -0.2%, 1.1%, and 1.4%, respectively.
    c. High correlation between employment and population: At the relatively large PDC level, jobs and population are highly correlated with correlation coefficients of 0.99 for both 2017 and 2045.
    d. Variation in employment growth: Bristol Construction District has only 3% of Virginia's 2017 employment and is, depending on the source, forecast to see its employment either increase (by 18%) or decrease (by 3%). This highlights forecast limitations mentioned in Section 1.4.
2. Concentrated employment growth: Virginia's employment in 2017 is concentrated in three PDCs with the highest populations: Northern Virginia (33%), Hampton Roads (20%) and Richmond Regional (14%).
    a. Employment growth in Virginia's urban crescent: These three PDCs (Northern Virginia, Hampton Roads, and Richmond Regional) account for 75% of the new jobs expected between 2017 and 2045 with the percentage rising to 80% if George Washington Regional is added to the list.
    b. Six (6) of 21 PDCs (Northern Virginia, Hampton Roads, Richmond Regional, Roanoke-Valley Alleghany, George Washington Regional, and Central Shenandoah) account for 85% of new jobs by 2045.
3. Employment growth sectors: More than half (54%-58%) of Virginia's jobs in 2017 are in five categories: Accommodation & Food Services; Health Care & Social Assistance; Retail Trade; Professional & Technical Services; and Government. Further, these five sectors account for between 57% and 61% of Virginia's forecast employment growth between 2017 and 2045.

4.3. Forecast for Household Income

1. Household income: Virginia household incomes, in real terms, are forecast to increase between 25% and 38% by 2045, with individual PDCs forecast to see increases ranging from 9% to 50% and VDOT Construction District increases ranging from 19% to 35%.
    a. Real household incomes are forecast to increase between 2017 and 2045 for all VDOT Construction Districts
    b. Estimates of 2017 incomes vary widely across Construction Districts, by a factor of more than 2 from the lowest to the highest. Only Northern Virginia Construction District has an estimated household income that exceeds the mean value for Virginia. Most Construction Districts are also below the median value. For both 2017 and 2045, only the Fredericksburg and Northern Virginia Construction Districts exceed the statewide median household income.
    c. In absolute terms (e.g., the difference between 2045 and 2017 incomes, all in year 2009 dollars), three of the nine VDOT Construction Districts (Fredericksburg, Culpeper, and Northern Virginia), all exceed the average statewide increase in median income by $2,243, $2,497, and $2,528 respectively.

4.4. Impact of Sociodemographic Trends on Transportation System and Associated Needs

- Impact of transportation investments on population growth: Transportation investments have the potential to support population growth and economic development, but only if other conditions which also support such growth are present.

- Published research indicates that investments in a heavy rail system along with appropriate zoning policies support and increase in population[1], while investments in roadways supported an increase in employment rate (but not total employment).[2] The likelihood of an investment having an impact on growth decreases if the proposed investment only marginally improves travel conditions, as opposed to an investment that renders a formerly inaccessible area accessible[3].

  In summary, the literature shows instances where investments in transportation led to an increase in employment rate (but not total employment)[4] and population[5]. However, because other factors such as immigration[6], economic incentives[7], school availability[8], and the presence of proximate competing employment centers[9] also affect location choice, a given investment in transportation may not necessarily affect a region's development pattern.

- Correlation between population and employment: While population and employment are highly correlated at the VDOT Construction District or PDC level, regional employment values are more volatile than regional population values. For the period 1975-2017, the changes in annual population growth rates by VDOT Construction District tended to be substantially smaller than the corresponding changes in annual employment growth rates.
- Transportation needs of aging population: While changes in transportation needs appear to vary by region, a common theme is that the population of Virginians age 65+ is increasing faster than that of other age groups. Related investments that support mobility for this group may be of interest, such as pedestrian facilities[10], assistance for persons who have trouble driving[11], fare policies for public transportation[12], and safety measures that specifically target older drivers[13].
- Impact of Amazon Headquarter 2 (HQ2) in Northern Virginia: A case study suggests that 2045 regional forecasts can be altered by a few percentage points by the unanticipated arrival of a large employer. Based on the Northern Virginia PDC where Amazon announced in November 2018 its forthcoming headquarters, the research team estimates that assuming the 94,321 direct and induced jobs are in place in 2045[14] and are all located in Northern Virginia, then population and employment for the VDOT Northern Virginia Construction District would be higher by amounts of 6.3% or 3.4% than would be the case without Amazon.
  - The same case study as above illustrates the magnifying impacts of changes in employment and population. The arrival of Amazon shows that each additional job can beget a series of impacts that include further employment growth (depending on the salaries provided by the original jobs), changes in demand for certain occupations, and changes in housing demand, all of which are magnified at the local level.

[1] John, K.E. Subway Expected to Reverse, Arlington Population Decline. The Washington Post, August 27, 1982.

[2] Zhao and Leung, 2018

[3] Meyer and Miller, 2013

[4] Zhao, Z.J. and Leung, W. Transportation Investment and Job Creation in Minnesota Counties. University of Minnesota, Minneapolis. Accessed April 12, 2019.

[5] John, K.E. Subway Expected to Reverse, Arlington Population Decline. The Washington Post, August 27, 1982. Accessed December 18, 2018.

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[7] Shearer, C., Shah, I., and Muro, M. Advancing Opportunity in Central Indiana, Brookings Institution, Washington, D.C., 2018. Accessed December 18, 2018.

[8] Cromartie, J., von Reichter, C., and Arthun, A. Factors Affecting Former Residents' Returning to Rural Communities, ERR-185, U.S. Department of Agriculture, Economic Research Service, Washington, D.C. Accessed February 11, 2020.

[9] Boarnet, M.G. and Haughwout, A.F. Do Highways Matter? Evidence and Policy Implications of Highways' Influence on Metropolitan Development, The Brookings Institution Center on Urban and Metropolitan Policy, 2000. Accessed April 12, 2019.

[10] DeGood, K. Aging in Place, Stuck without Options: Fixing the Mobility Crisis Threatening the Baby Boom Generation. Transportation for America, Washington, D.C., 2011. Accessed March 26, 2019.

[11] National Aging and Disability Transportation Center (NADTC). Older Adults & Transportation: Unique issues related to older adults and transportation. 2019. Accessed March 26, 2019.

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[13] Getzmann, S., Arnau, S., Karthaus, M., Reiser, J.R., and Wascher, E. Age-Related Differences in Pro-Active Driving Behavior Revealed by EEG Measures. Frontiers in Human Neuroscience, Volume 12, 2018. Accessed May 10, 2019.

[14] Fuller, S. S. and Chapman, J. The Economic and Fiscal Impacts of Locating Amazon's HQ2 in Arlington County, Virginia. Report Prepared for the Virginia Economic Development Partnership. November 8, 2018. Accessed April 23, 2019.

- The arrival of Amazon may add approximately 59,000 jobs by 2030[1] and 94,000 jobs by 2040[2]. These jobs include those directly employed by Amazon (cited as 25,000 by the former source and 50,000 by the latter source) and the ones created by ripple effects due to its presence.
- For the specific localities affected by Amazon, economists expect Amazon to generate substantial additional employment and population growth from induced, indirect, and spinoff effects[3]. These effects are affected by the Amazon salaries; for example, Fuller and Chapman (2018) suggest that with an increase in Amazon salaries from a presumed value of $150,000 to a higher value of $200,000 will lead to an extra 5,177 induced jobs.
- Economists say although Amazon's arrival will intensify job growth and housing demand (particularly in Arlington), the net impact may be a 6 to 13% increase compared to the population and growth rates the Washington region has experienced over the last 20 years[4].
- Amazon could enable Northern Virginia and the Commonwealth to retain more highly educated and skilled employees, countering recent patterns of outmigration[5].
- Investments in higher education in Northern Virginia will increase the number of graduates and doctoral candidates in information technology and related fields to provide the employees needed by Amazon and related companies[6].
- The arrival of Amazon will allow Arlington and the Commonwealth to continue further diversifying their economies toward less reliance on federal employment[7].
- With Amazon employees' expected average annual income of $150,000, average household incomes of National Landing residents may rise over the next five to ten years[8].
- An existing lack of affordable housing in Arlington may be exacerbated by HQ2 [9]. A shortage of affordable housing may cause lower income households to move farther out and face longer commutes to their jobs.

▪ Impact of large employers on transportation demand: A change in these forecasts may portend a change in travel demand. The arrival of a large employer, for example, in Arlington County may not only increase population and employment by an estimated 6% and 3% (relative to forecasts made prior to knowledge of this employer arriving) but may also increase demand for transit or vehicle trips, which could be exacerbated by a shortage of affordable housing[10].

[1] Chmura Economics and Analytics Economics and Analytics. Economic Impact of Amazon's Major Corporate Headquarters in Virginia and the Washington MSA. December 7, 2018. Accessed April 23, 2019.

[2] Fuller, S. S. and Chapman, J. The Economic and Fiscal Impacts of Locating Amazon's HQ2 in Arlington County, Virginia. Report Prepared for the Virginia Economic Development Partnership. November 8, 2018. Accessed April 23, 2019.

[3] Stephen S. Fuller Institute for Research on the Washington Region's Economic Future, George Mason University. November 18, 2018. What Does Amazon's HQ2 Mean for the Washington Region? Accessed April 18, 2019.

[4] Stephen S. Fuller Institute for Research on the Washington Region's Economic Future, George Mason University. What Does Amazon's HQ2 Mean for the Washington Region?, November 18, 2018.

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[6] Woolsey, A. Prepare for impact: Amazon HQ2 officially coming to Northern Virginia, Fairfax County Times, November 13, 2018. Accessed April 15, 2019.

[7] Stephen S. Fuller Institute for Research on the Washington Region's Economic Future, George Mason University. What Does Amazon's HQ2 Mean for the Washington Region?, November 18, 2018.

[8] Fleishman, G. Only Half of Jobs at Amazon's HQ2 in Tech, Report Says, with the Balance in Support Positions. Fortune, November 21, 2018. Accessed April 15, 2019.

[9] Jan, T., and Orton, K. Northern Virginia Property Owners are Delighted Amazon HQ2 is Moving In. Renters, First Time Buyers and Low-Income Residents aren't, The Washington Post, November 13, 2018. Accessed April 15, 2019.

[10] Sullivan, P. GMU Panel: Don't expect Amazon to change the region all at once. The Washington Post, December 14, 2018. Accessed April 15, 2019.

APPENDIX 2-A: JURISDICTIONS ASSOCIATED WITH EACH VDOT CONSTRUCTION DISTRICT

Construction District	Jurisdictions
Bristol	Bland, Buchanan, Dickenson, Grayson, Lee, Russell, Scott, Smyth, Tazewell, Washington, Wise, Wythe, Bristol, Norton
Salem	Bedford, Botetourt, Carroll, Craig, Floyd, Franklin, Giles, Henry, Montgomery, Patrick, Pulaski, Roanoke County, Galax, Martinsville, Radford, Roanoke City, Salem City
Lynchburg	Amherst, Appomattox, Buckingham, Campbell, Charlotte, Cumberland, Halifax, Nelson, Pittsylvania, Prince Edward, Danville, Lynchburg
Richmond	Amelia, Brunswick, Charles City, Chesterfield, Dinwiddie, Goochland, Hanover, Henrico, Lunenburg, Mecklenburg, New Kent, Nottoway, Powhatan, Prince George, Colonial Heights, Hopewell, Petersburg, Richmond City
Hampton Roads	Accomack, Isle of Wight, James City, Northampton, Southampton, Surry, Sussex, York, Greensville, Chesapeake, Emporia, Franklin, Hampton, Newport News, Norfolk, Poquoson, Portsmouth, Suffolk, Virginia Beach, Williamsburg
Fredericksburg	Caroline, Essex, Gloucester, King and Queen, King George, King William, Lancaster, Mathews, Middlesex, Northumberland, Richmond County, Spotsylvania, Stafford, Westmoreland, Fredericksburg
Culpeper	Albemarle, Culpeper, Fauquier, Fluvanna, Greene, Louisa, Madison, Orange, Rappahannock, Charlottesville
Staunton	Alleghany, Augusta, Bath, Clarke, Frederick, Highland, Page, Rockbridge, Rockingham, Shenandoah, Warren, Buena Vista, Covington, Harrisonburg, Lexington, Staunton, Waynesboro, Winchester
Northern Virginia	Arlington, Fairfax County, Loudoun County, Prince William, Alexandria, Fairfax City, Falls Church, Manassas, Manassas Park

APPENDIX 2-B: JURISDICTIONS ASSOCIATED WITH EACH MODIFIED PLANNING DISTRICT COMMISSION

Most of Virginia's 133 independent cities and counties are in exactly one of Virginia's 21 PDCs, with seven exceptions[1]: Cumberland County and Nottoway County are not in any PDC, Chesterfield County and Charles City County are in two PDCs (Crater and Richmond Regional), Gloucester County is in two PDCs (Hampton Roads and Middle Peninsula), Surry County is in two PDCs (Crater PDC and Hampton Roads), and Franklin County is in two PDCs (Roanoke Valley-Alleghany Regional Commission and West Piedmont). To avoid double counting adjustments were made to include every jurisdiction within exactly one PDC. The following table summarizes the Jurisdictions included in each Modified PDC.

Modified Planning District Commission	Jurisdictions
Lenowisco	Lee, Norton, Scott, Wise
Cumberland Plateau	Buchanan, Dickenson, Russell, Tazewell
Mount Rogers	Bland, Bristol, Carroll, Galax, Grayson, Smyth, Washington, Wythe
New River Valley	Floyd, Giles, Montgomery, Pulaski, Radford
Roanoke Valley-Alleghany	Alleghany, Botetourt, Covington, Craig, Franklin County , Roanoke City , Roanoke County , Salem
Central Shenandoah	Augusta, Bath, Buena Vista, Harrisonburg, Highland, Lexington, Rockbridge, Rockingham, Staunton, Waynesboro
Northern Shenandoah	Clarke, Frederick, Page, Shenandoah, Warren, Winchester
Northern Virginia	Alexandria, Arlington, Fairfax City, Fairfax County, Falls Church, Loudoun, Manassas, Manassas Park, Prince William
Rappahannock-Rapidan	Culpeper, Fauquier, Madison, Orange, Rappahannock
Thomas Jefferson	Albemarle, Charlottesville, Fluvanna, Greene, Louisa, Nelson
Central Virginia	Amherst, Appomattox, Bedford, Campbell, Lynchburg
West Piedmont	Danville, Henry, Martinsville, Patrick, Pittsylvania
Southside	Brunswick, Halifax, Mecklenburg
Commonwealth Regional Council	Amelia, Buckingham, Charlotte, Cumberland, Lunenburg, Nottoway, Prince Edward
Richmond Regional	Charles City, Chesterfield, Goochland, Hanover, Henrico, New Kent, Powhatan, Richmond City
George Washington	Caroline, Fredericksburg, King George, Spotsylvania, Stafford
Northern Neck	Lancaster, Northumberland, Richmond County , Westmoreland
Middle Peninsula	Essex, Gloucester, King and Queen, King William, Mathews, Middlesex
Crater	Colonial Heights, Dinwiddie, Emporia, Greensville, Hopewell, Petersburg, Prince George, Surry, Sussex
Accomack-Northampton	Accomack, Northampton
Hampton Roads	Chesapeake, Franklin City, Hampton, Isle of Wight, James City, Newport News, Norfolk, Poquoson, Portsmouth, Southampton, Suffolk, Virginia Beach, Williamsburg, York

APPENDIX 2-C: DEVELOPMENT OF POPULATION, EMPLOYMENT, AND HOUSEHOLD INCOME ESTIMATES AND PROJECTIONS

After obtaining population, employment, household income estimates and projections by locality, the data were arranged by VDOT district. Then, for each district, the current population (for year 2017), the forecast population (for year 2045), and the change in population by age group, on both a nominal and a percentage basis, were calculated. Because of how these data sets are organized, adjustments were needed for the population and income forecasts. No adjustments were needed for the employment forecasts except to realize that employment forecasts from different sources are not necessarily directly comparable.

[1] Virginia Association of Planning District Commissions. PDC Directory. Accessed September 6, 2018.

2-C-1: Adjustments for Population Forecasts

The Weldon Cooper Center for Public Service provides age-based forecasts for year 2040 rather than year 2045. The provider of these forecasts suggested that to obtain 2045 values for individual units (e.g., PDCs or Construction Districts), one could multiply the 2040 distribution by age by the 2045 values in order to obtain "quick but still o.k." values. Accordingly, for each Construction District, the age distributions for under age 20, age 20-64, and age 65+ that had been developed for year 2040 were multiplied by the 2045 total population values. For example, for year 2040, the percentage of persons age 65+ in the Bristol Construction District was forecast to be 21.1%, and the total population of the Bristol Construction District for year 2045 is forecast to be 325,987. The product of these two values yields a 2045 forecast of 80,910 persons age 65+ for the Bristol Construction District.

Appendix 2 Table C-1: Example of Interpolated Age Forecasts for Year 2045 by VDOT Construction District[1]

Construction District	under 20	20-64	65 +
Bristol	68,931	176,146	80,910
Salem	171,928	406,607	174,397
Lynchburg	99,985	229,885	93,552
Richmond	390,890	895,031	311,055
Hampton Roads	479,434	1,117,088	383,636
Fredericksburg	177,954	373,128	134,529
Culpeper	131,454	296,097	116,113
Staunton	165,833	361,225	146,755
Northern Virginia	909,978	2,094,567	541,710
Statewide	2,594,493	5,947,411	1,986,913

2-C.2: Adjustments for Income Forecasts

The following adjustments for income forecasts were made:

- As is the case with employment, the household income reported by Woods & Poole is typically higher than that of other sources such as the U.S. Census Bureau. Formally, the Woods & Poole income includes not only wages and salaries but also "proprietors' income, rental income of persons, dividend income, personal interest income, and transfer payments less personal contributions for social insurance." Woods & Poole reports that income as reported by the U.S. Census Bureau excludes certain items such as the value of food stamps, the value of medical payments, and the "imputed rental value of owner-occupied housing." Another factor is that whereas Woods & Poole reports the mean household income, other sources may report the median household income. For these reasons, it is not surprising that the mean household income in Virginia for 2017 ($120,910) is considerably higher than the median household income reported by the U.S. Census ($68,766)—even though the former is in 2009 dollars and the latter is in 2017 dollars.[2]
- For household incomes reported by Moody's Analytics, there are four methodological differences that affect how these data are interpreted with respect to incomes reported by Woods & Poole. First, although Virginia has 133 independent cities and counties in total, Moody's only reports data for 105 geographical areas in Virginia, which in total represent the entire Commonwealth. Most (82) of Moody's areas correspond directly with a Virginia jurisdiction; for example, Moody's provides an income for the independent city of Virginia Beach. However, about one-fifth (23) of Moody's 105 areas are an aggregation of two or more Virginia jurisdictions. For example, Moody's provides a single income for the combined area of Roanoke County plus the City of Salem (but the City of Roanoke is reported separately); another example is that the cities of Colonial Heights and Petersburg, along with Dinwiddie County, are reported as a single area. As shown in Table B-2, the county that represented these combined areas was used to assign the area to the appropriate VDOT Construction District. For instance, because Prince George County is in the VDOT Richmond Construction District, the City of Hopewell is also placed in this same Construction District.

[1] Based on data from the Weldon Cooper Center for Public Service.
[2] U.S. Census Bureau, Woods and Poole

Appendix 2 Table C-2: Correspondence Between Moody's Areas and the Assigned Jurisdiction

Moody's Combined Area	Assigning Jurisdiction
Albemarle + Charlottesville (VA)	Albemarle County, Va
Alleghany, Clifton Forge + Covington (VA)	Alleghany County, Va
Augusta, Staunton + Waynesboro (VA)	Augusta County, Va
Campbell + Lynchburg (VA)	Campbell County, Va
Carroll + Galax (VA)	Carroll County, Va
Dinwiddie + Col. Hts + Peters (VA)	Dinwiddie County, Va
Fairfax County, Fairfax City + Falls Church (VA)	Fairfax County, Va
Frederick + Winchester (VA)	Frederick County, Va
Greensville + Emporia (VA)	Greensville County, Va
Henry + Martinsville (VA)	Henry County, Va
James City + Williamsburg (VA)	James City County, Va
Montgomery + Radford (VA)	Montgomery County, Va
Pittsylvania + Danville (VA)	Pittsylvania County, Va
Prince George + Hopewell (VA)	Prince George County, Va
Prince William, Manassas + Manassas Park (VA)	Prince William County, Va
Roanoke County + Salem (VA)	Roanoke County, Va
Rockbridge, Buena Vista + Lexington (VA)	Rockbridge County, Va
Rockingham + Harrisonburg (VA)	Rockingham County, Va
Southampton + Franklin City (VA)	Southampton County, Va
Spotsylvania + Fredericksburg (VA)	Spotsylvania County, Va
Washington + Bristol (VA)	Washington County, Va
Wise + Norton (VA)	Wise County, Va
York + Poquoson (VA)	York County, Va

- Moody's reports forecast incomes in current year dollars. For example, Moody's forecasts the 2045 median income for Appomattox County to be $109,710—in year 2045 dollars. Accordingly, a customized Virginia-specific statewide deflator table was provided by Moody's staff[1] for a base year of 2009, where one multiplies dollars reported in any other year by the deflator to obtain forecast income in 2009 dollars. Because the deflator for year 2045 is 0.5229, the Appomattox County median income of $109,710 (in 2045 dollars) is multiplied by 0.5229 to obtain a 2045 forecast median income of $57,367 (in 2009 dollars). The value of 2009 dollars was chosen because the incomes provided by Woods & Poole[2] are also in 2009 dollars. The statewide deflator is an estimate in that one could also purchase deflators that are specific to certain metropolitan areas.
- Woods & Poole reports the mean household income, whereas Moody's reports the median household income. In locations where there were a few households with very large or very small household incomes, there could be a difference between the mean and the median incomes. Mean values are more influenced by extreme values in a distribution than median values.
- Moody's and Woods & Poole do not define income in the same manner. Moody's indicates that for a definition of income, one should examine the corresponding "driver" of this income, which Moody's[3] then notes, is based on four sources: "the U.S. Census Bureau's (BOC) annual American Community Survey (ACS), Decennial Census, the Current Population Survey, and the Small Area Income and Poverty Estimates from the BOC." The U.S. Census Bureau then reports that personal income includes eight categories of income, abbreviated here as salaries, self-employment,

[1] Kamins, A. Email to John S. Miller. January 10, 2019.

[2] Woods & Poole Economics, Inc. 2018 State Profile, District Of Columbia, Maryland, and Virginia, CD-ROM Technical Documentation. Washington, DC, 2018.

[3] Moody's Analytics. U.S. County Forecast Database, New York, NY, 2019.

interest/royalties/net rental income, social security income, disability income, public assistance income, retirement income, and all other income (e.g., child support). To be clear, the U.S. Census Bureau includes social security retirement income (e.g., income for individuals who have reached a certain age of 62 or older and have elected to start receiving such income), supplemental security income (abbreviated as "SSI") which "guarantees a minimum level of income for needy aged, blind, or disabled individuals", and public assistance income (which is Temporary Assistance to Needy Families ("TANF"); this last program was colloquially described as "welfare" until 1996 when TANF replaced a program in place from 1935 to 1996 known as Aid to Families with Dependent Children (Center on Budget and Policy Priorities, 2018). While the U.S. Census Bureau (2018c) does not explicitly state whether it includes social security disability income (SSDI), the Bureau notes that it includes in its income "permanent disability insurance payments made by the Social Security Administration prior to deductions for medical insurance" which, based on a review of how the Social Security Administration (2018) defines SSDI, suggests that SSDI is included in incomes from the U.S. Census Bureau and hence would be part of the Moody's[1] data set.

- Although these categories are numerous, note that as suggested by Woods & Poole, the incomes based on the U.S. Census (such as Moody's) tend to be smaller than those of Woods & Poole. Examination of incomes for one county in Virginia supports this viewpoint. For Appomattox County, in 2009 dollars, an approximate 2018 household income was approximately $45,105 (Moody's Analytics), $48,069 (U.S. Census Bureau), and $78,468 (Woods & Poole) as shown in the right column of Table B-3.

Appendix 2 Table C-3: Current Household Incomes for Appomattox County

Source	Period	Type	Income (year $)	Income (2009 $)
Woods & Poole	2017	Mean	$78,468 (2009 $)	$78,468
U.S. Census Bureau (2018d)	2013-2017[2]	Median	$54,875 (2017 $)	$48,069
Moody's Analytics	2017	Median	$50,851 (2017 $)	$45,105

- Woods & Poole reports incomes in 2009 dollars, this is not the case for the other two sources, thus, the Moody's income in 2017 dollars was deflated using the value provided by staff and the American Community Survey data was deflated using the consumer price index (U.S. Bureau of Labor Statistics) so that 2009 income would be available for all three data sources.
- For each modified PDC, a weighted median household income was computed in a manner similar to that used for the Woods & Poole data. After the incomes for each Moody's area were converted to 2009 dollars, for each area in the PDC, the product of the area's households and income was summed and then divided by the number of households in the PDC as provided by Moody's Analytics. A similar process was followed for aggregating incomes by VDOT Construction Districts. Moody's Analytics frequently updates these data; the household data in this report were updated December 21, 2018 and the income data were updated January 4, 2019. The authors have reported the estimated statewide median income in this manner, where the median household income (by jurisdiction) is multiplied by the number of households for each jurisdiction and then the total is divided by all households in the Commonwealth.

(This estimated median was chosen for consistency with the geography used for obtaining specific Construction District and PDC values. It is also possible to obtain, from a separate data series, what Moody's reports as a statewide median, which is not disaggregated by jurisdiction. The statewide median from this statewide series differs from the estimated median (based on the county series) by approximately 7% for year 2017 and 4% for year 2045. Possible reasons for the difference include the fact that the statewide deflator provided by Moody's to the researchers is an estimate (e.g., different deflators could be used for different urban areas) and the fact that the household weighted estimate for a median is not identical to computing a true median value.)

[1] Moody's Analytics. U.S. County Forecast Database, New York, NY, 2019.

[2] For jurisdictions under 20,000 people, the American Community Survey obtains data over a 5 year period.

2-C.3: Feasibility of Comparing Employment Forecasts from Different Sources

The employment data are based on the VDOT Construction District where the job is located and include wage and salary workers, proprietors, private household employees, and "miscellaneous workers"; because proprietors and military workers are included [as well as both full and part-time jobs], employment may be higher from this database than from other sources[1]. Such disparities in employment definitions are not unusual; for example total 2016 jobs in the U.S. obtained from the Bureau of Economic Analysis (almost 150 million) is about 6% higher than jobs obtained from the Bureau of Labor Statistics (almost 142 million) because the latter does not include (or fully include) certain types of employment such as religious organizations, rail transportation, some nonprofits with fewer than four employees, and military employees[2].

Woods & Poole defines households as occupied housing units and excludes persons in "group quarters" such as university dormitories, prisons, or "military barracks." Because Woods & Poole reports a "mean household income" which is the "total personal income less estimated income of group quarters population divided by the number of households", the authors computed a weighted mean household income for each PDC or Construction District. This weighted mean household income was computed by multiplying the number of households for each city or county by the mean household income for each such jurisdiction to get a total household income by jurisdiction, summing these total income values by PDC or Construction District, and then dividing by the corresponding number of households for the PDC or Construction District.

2-C.4: Explanation of Differences in Employment Forecasts

While it is not possible to know which employment forecast will prove to be most accurate in 2045, it is possible to examine the reasons for the disparity in employment forecasts. Both Woods & Poole[3] and IHS Markit[4] forecast an increase in employment statewide (44.1% and 18.2%), respectively—but within professions, some forecasts differ substantially. While there is a difference of 26 percentage points between these statewide forecasts, there are some industrial classifications where these two sources are more similar: arts, entertainment, and recreation (45% and 30%); manufacturing (decreases of 4% and 6%); and government (24% and 10%). (The Woods & Poole government category includes the three categories of state and local, federal civilian, and federal military; IHS Markit government is a single category of public administration.) Notable differences include health care and social assistance (increases of 90% and 33% for forecast), professional and technical services (61% and 31%), retail trade (46% and 5%), other services (examples of which are churches, dry cleaning, pet care, dating services, machinery repairing, and advocacy[5] (56% and 2%), and real estate & rental & leasing (97% and 55%). If these last five differences were eliminated, then overall the percentage difference for these two sources for statewide employment would be between 7 and 9 percentage points depending on the exact manner of tabulation, rather than 26 percentage points.

The two biggest contributors to these different statewide forecasts in total employment are health care and retail trade. These are then followed by five employment categories that are much closer to each other (in terms of their importance to the difference in statewide employment as forecast by Woods & Poole and IHS Markit): professional and technical services; other services (e.g., churches, dry cleaning, pet care, dating services, machinery repairing, and advocacy [Woods & Poole]); accommodation & food services; government; and administrative & waste services.

[1] Woods & Poole Economics, Inc. Virginia, Maryland, and The District of Columbia, 2018. State Profile, State and County Projections to 2050. Washington, 2018.

[2] Bureau of Economic Analysis. Local Area Personal Income and Employment Methodology, Washington, DC, 2017. Accessed December 12, 2018.

[3] Woods & Poole Economics, Inc. Virginia, Maryland, and The District of Columbia, 2018 State Profile, State and County Projections to 2050. Washington, DC, 2018.

[4] Jeafarqomi, K. Email to John S. Miller. December 13, 2018.

[5] Woods & Poole Economics, Inc. 2018 State Profile, District Of Columbia, Maryland, and Virginia, CD-ROM Technical Documentation. Washington, DC, 2018.

Differences in employment forecasts by sector can be magnified in PDCs with relatively small employment totals. For example, consider Accomack-Northampton, which showed a 27% increase in employment (Woods & Poole) and a 26% decrease in employment by IHS Markit for the period 2017-2045. The latter 26% decrease in employment would change to an 8% increase in employment if differences in just four employment categories were eliminated: health care (which more than doubles according to Woods & Poole but shrinks by 18% based on IHS Markit), government employment (a 16% increase versus a 34% decrease, manufacturing (a 5% increase versus a 32% decrease), and other services (a 32% increase versus a 50% decrease).

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