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

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FOR MORE INFORMATION

Visit vtrans.virgnia.gov for additional details, updates, and documentation about the VTrans development process. Please contact the Statewide Transportation Planning (STP) Team at the Office of Intermodal Planning and Investment to request an alternative format.

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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
CoM	Coefficient of Imitation
CoN	Coefficient of Innovation
CoSS	Corridor of Statewide Significance
COVID-19	Coronavirus Disease 2019
CTB	Commonwealth Transportation Board
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
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
TNC	Transportation Network Company
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 have 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
- Tailpipe Emissions – By-products of internal combustion engines
- 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[7] – 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.
- Robotaxi – Also known as self-driving taxi or driverless taxi, is an autonomous car (SAE automation level 4 or 5) operated by and for a ridesharing company.
- Sea Level Rise – Incremental rising of the mean high water level over time.
- Scrappage (vehicles) rate – The portion of a specific age cohort of vehicles that are removed from the road (scrapped) each year, typically due to mechanical failure or economic unsustainability.
- 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.[8]
- Storm Surge[9] – Abnormal rise in seawater level during a storm, measured as the height of the water above the normal predicted astronomical tide.
- Vulnerability[10] – 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[11] – 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

[7] 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 the Technical Memorandum for the VTrans Vulnerability Assessment.

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

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

[10] 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 the Technical Memorandum for the VTrans Vulnerability Assessment.

[11] National Safety Council

CHAPTER 1. PURPOSE OF THE TECHNICAL GUIDE

This Technical Guide is a synthesis of technical methods and processes used to execute 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. 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 is a separate Technical Guide for Chapters 4 and 5 of the VTrans Policy Guide.

The purpose of developing a Risk & 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:

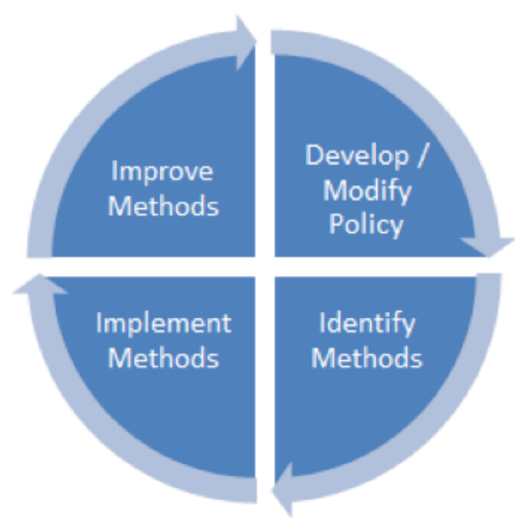
- Uncertainties: There are several known uncertainties related to different datasets used for the execution of the Policy for the Development and Monitoring of the VTrans Long-term Risk & Opportunity Register. These uncertainties include, but are not limited to, the following:
  - Policy uncertainty: Globally, countries are making commitments to further accelerate certain macrotrends. For example, accelerating the adoption of electric vehicles or decelerating the risk of 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.

- 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 Goal Metrics 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 Goal Metric 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, data collection, and reporting tools. To the extent that any such improvements modify or affect the policy, public review and CTB's approval will be sought.

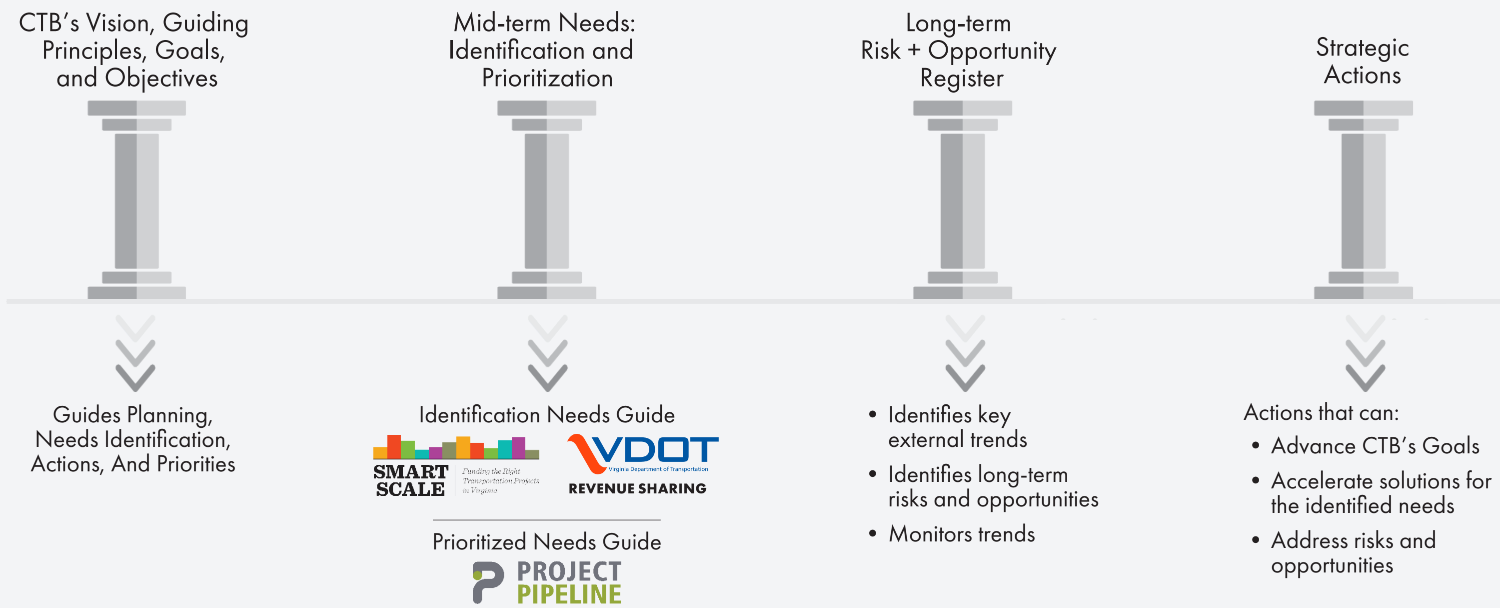
Figure 1-1: Opportunities for Continuous Improvement



CHAPTER 2. INTRODUCTION TO VTRANS – VIRGINIA'S TRANSPORTATION PLAN

VTrans is the plan to advance the Commonwealth Transportation Board's (CTB) vision for multimodal 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 improvement 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 Chapter 6 of the VTrans Policy Guide.

Figure 2-1: Major Components of VTrans – Virginia's Transportation Plan



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. The CTB updated and adopted the VTrans Vision, Guiding Principles, Goals, and Objectives in 2025.

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 Horizon 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

CHAPTER 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 are 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 3-1: 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
- Technology
- Consumption
- Socio-demographics

Step 2: Develop Metrics for CTB Goals

Priorities associated with CTB Goals are identified:
- Goal A: Transportation System Safety
- Goal B: System Preservation
- Goal C: Economic Competitiveness through Travel Time Reliability
- Goal D: Inter-Connected Systems and Services
- Goal E: Environmental Stewardship

Step 3: Estimate Impact of Macrotrends on Goal Metrics

A range of potential impacts of the megatrends (Step 1) on the Goal Metrics (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, Action on Modifying the VTrans Vision, Guiding Principles, Goals, and Objectives and Action on Performance Measures and Targets, April 15, 2025.

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 3.1-1 below. These are referred to as VTrans Megatrends and VTrans Macrotrends to differentiate them from other mega and macrotrends that exist.

Table 3.1-1: VTrans Mega- and Macrotrends

MEGATREND 1: CLIMATE
Macrotrend # 1: Increase in Flooding Risk[3,4]
MEGATREND 2: TECHNOLOGY
Macrotrend # 2: Adoption of Highly Autonomous Vehicles
Macrotrend # 3: Adoption of Electric Vehicles
Macrotrend # 4: Growth in Shared Mobility
MEGATREND 3: CONSUMPTION
Macrotrend # 5: Growth in E-commerce
Macrotrend # 6: Greater Automation of Goods and Services
MEGATREND 4: SOCIO-DEMOGRAPHICS
Macrotrend # 7: Growth of Professional Services 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, available at Issu.com.

3 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.

4 Definition of 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.

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:[1]

- Emissions of heat-trapping gases

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 provides six emission-based scenarios aligned with conditional

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

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

- **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 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. The scenarios also rely on historical flooding documented by VDOT.

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

Description: This macrotrend captures the projected adoption of advanced vehicle automation technologies in personal and commercial vehicles. This analysis relies on automation categorization developed by the Society of Automotive Engineers (SAE).[1] Please refer to the definitions in Section 1 of this document.

Highly autonomous vehicles, Levels 3 and 4, both primarily face challenges stemming from an ambiguous regulatory framework and substantial liability assigned to manufacturers for accidents occurring while automation is active.[2] These obstacles outweigh technological distinctions between the two levels. Hence, estimates for the uptake of highly autonomous vehicles in the modeling approach treat Levels 3 and 4 collectively, recognizing that their adoption and manufacturing may overlap or compete within the market.

The modeling approach incorporates sales projections, stock turnover, scrappage dynamics, and behavioral assumptions such as willingness to pay and technology cost decline.

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.[3]
- Industry-wide push and investments towards development of automated vehicles.[4]
- Consumer preferences for safety and openness to vehicle technology.[5]

[1] SAE International

[2] Fuel for Thought: Waiting for Autonomy, S&P Global

[3] How AI and automation are changing our driving experience, World Economic Forum

[4] Autonomous vehicles moving forward: Perspectives from industry leaders, McKinsey & Company

[5] Autonomous vehicles: On the road to rising consumer trust, S&P Global

Data Sources:

- ADAS sales data (2015-2023) by Mitre.org[6]
- Scrappage trends: Green and Leard (2024)[7]
- AV Adoption Curves: Bansal & Kockelman (2017)[8]; Mishra et al. (2019)[9]
- Commercial Vehicles and Firms in Virginia: FMCSA[10]

Calculations:

A. Estimate the market penetration of personal/passenger AVs for years 2020 to 2050.

Step 1: Estimate New sales of vehicles equipped with Level 1 and Level 2 technologies.

Historical sales data of vehicles with the above technologies from 2015-2023 was used to establish a baseline. Future sales were projected using a linear growth curve with 100% saturation occurring at different times depending on the technology, based on industry studies.

Step 2: Stock Turnover Modeling with Variable Scrappage Rate

Vehicle stock was projected annually using the formula:

$$Stock\_Tech\%_t = Stock\_Tech\%\ (t - 1) * (1 - S_t) + NewSales\_Tech\%_t * S_t$$

Where,

$Stock\_Tech\%_t$ = Share of the total vehicle fleet equipped with the technology in year 't'

$Stock\_Tech\%\ (t - 1)$ = Share of the fleet equipped with the technology in the previous year

$NewSales\_Tech\%_t$ = Share of newly sold vehicles equipped with the technology in year 't'

S_t = Scrappage rate in year 't', i.e., the fraction of vehicles retired from the fleet that year

$(1 - S_t)$ = Proportion of vehicles that remain in the fleet from the previous year

This formula accounts for both carryover vehicles from the previous year and new vehicle sales, weighted by annual fleet turnover. Estimations on fleet turnover were based on the following assumptions:

- The lifespan of vehicles increases annually by 0.67% based on national trends (source: Green & Leard, 2024), resulting in a declining scrappage rate.
- Stock penetration lags sales due to the probabilistic decay of older non-ADAS vehicles.

Step 3: Introducing Market Cannibalization Effects from Level 3/Level 4 Autonomous Vehicles

Assuming commercial readiness of these technologies by 2030 based on market studies, a portion of would-be Level 2 vehicle adopters shift to Level 3/Level 4. This share of cannibalization is defined as

$$\gamma_{L3/L4(t)} = WillingnessToPay_t * (1 - PriceFactor_t)$$

Where,

$\gamma_{L3/L4(t)}$ = Cannibalization factor

$WillingnessToPay_t$ = Consumer's Willingness-to-Pay in year 't'

$PriceFactor_t$ = Annual Technology Price Reduction in year 't'

- Price Factor (or Annual Technology Price Reduction) in year 't' = Starts at 1 (full tech cost) and declines each year based on assumed (scenario-based) cost reduction.
- Scenarios are defined by an annual increase in Willingness-to-Pay (WTP) and annual decrease in Annual Technology Price Reduction.
  - Low: 0% WTP growth, 5% cost reduction
  - Medium: 5% WTP growth, 5% cost reduction
  - High: 10% WTP growth, 10% cost reduction

[6] PARTS: Market Penetration of Advanced Driver Assistance Systems (ADAS), MITRE Corporation

[7] Trends in scrappage and survival of U.S. light-duty vehicles, Green & Leard, 2024

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

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

[10] Motor Carrier Census System. FMSCA. Accessed in March 2025

Step 4: Estimating New-Sales of Level 3/Level 4 AVs and adjusted Level 2 AVs (ADAS) Sales

$NewSales_{L3/L4(t)} = BaseADAS_t * \gamma_{L3/L4(t)}$

Where,

$NewSales_{L3/L4(t)}$ = Share of all new vehicle sales in year 't' that are equipped with Level 3 or Level 4 automation

$BaseADAS_t$ = Share of all new vehicles in year t equipped with any form of advanced driving assistance (Level 2 AVs)

$\gamma_{L3/L4(t)}$ = Cannibalization factor in year t; the proportion of ADAS-intending buyers who opt for Level 3/Level 4 instead of L2 and is calculated using the formula below

$NewSales_{L2(t)} = BaseADAS_t * (1 - \gamma_{L3/L4(t)})$

Where,

$NewSales_{L2(t)}$ = Adjusted share of new vehicles sold in year 't' that are only equipped with Level 2(ADAS) features.

$(1 - \gamma_{L3/L4(t)})$ = Remaining share of ADAS adopters who do not shift to Level 3/Level 4 AVs.

Step 5: Stock Penetration for Level 3/Level 4 and adjusted Level 2 AVs (ADAS)

Stock levels are updated using the same turnover formula applied above, with respective new-sales percentages and dynamic scrappage rates for each scenario.

B. Estimate the market penetration of heavy-duty commercial AVs for the years 2021 to 2050.

1. Obtain data related to motor carriers in Virginia as of December 27, 2024.
2. Utilize the fields 'Number of Power Units' (equivalent of vehicles) and 'Number of Drivers' to conduct a k-means clustering3 to categorize 23,492 motor carriers as 'small,' medium,' or 'large.'
3. 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 3.1.2-1 by technology and adoption scenario type.
4. 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).
5. 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 2050. Estimates for low and high scenarios were generated using standard deviation.

Table 3.1.2-1: Estimated Commercial Readiness Year of Heavy-Duty Autonomous Technologies

Commercial Vehicle Technology	Commercial Readiness Year	Adoption Curve Type
Automated Manual Transmission	2006	Optimistic
Predictive Cruise	2016	Baseline
Adaptive Cruise	2019	Baseline
Platooning	2030	Conservative
Level 4 Automation	2035	Conservative

Results of the estimated market penetration of private light-duty and commercial heavy-duty autonomous vehicles are shown in Table 3.1.2-2 on the next page.

Table 3.1.2-2: Estimated Market Penetration of Vehicle Automation in Year 2050 by Vehicle Automation Levels

Vehicle Automation Levels	Estimated Market Penetration of Vehicle Automation Levels		
	Low Estimate	Medium Estimate	High Estimate
Passenger Vehicles			
Level 1	84%	88%	91%
Level 2	77%	82%	86%
Level 4	4%	11%	40%
Commercial Vehicles			
Level 0	74%	87%	100%
Level 1- Adaptive Cruise Control	38%	52%	65%
Level 1 and 2 Platooning	9%	23%	37%
Level 4	2%	15%	28%

Assumptions

- Market penetration rates are based on the willingness to pay and expected reductions in technology costs over time. In practice, adoption will vary across automation levels, with overlapping transitions among all AV technologies.
- Vehicle fleet turnover is modeled using scrappage rates that evolve with changes in average vehicle lifetime, influencing the pace at which new technologies replace older vehicles in stock.
- Adoption estimates incorporate substitution effects, with a portion of Level 2 buyers shifting to Level 3/Level 4 as availability, affordability, and acceptance improve.
- 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 2050.

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. They also may require additional investment in infrastructure, such as electric vehicle chargers to support their operations.

Drivers:

- Technological advancements in EV battery technology[1]
- Increased vehicle availability of EVs[2]
- Decreasing manufacturing costs[3]
- Growth in national charging infrastructure[4]

Data Sources:

- Market penetration of EVs from 2021-2050: Virginia Energy Policy Simulator
- Reduction in CO2e emissions due to EVs: Virginia Energy Policy Simulator

[1] Trends in electric vehicle batteries, International Energy Agency.

[2] EV Model Availability and Sales, Argonne National Laboratory.

[3] Trends in electric car affordability, International Energy Agency.

[4] Electric Vehicle Charging Infrastructure Trends, Alternative Fuels Data Center, U.S. Dept. of Energy

Calculations:

1. Estimate the market penetration of EVs from 2021-2050 based on three policy scenarios: Federal Policy Repeal and Rollback (FPR), Pre-Administration change (PAC) or January 2025 frozen policies and Nationally Determined Contribution (NDC), from the Virginia Energy Policy Simulator (EPS) Tool.[5]
2. The scenarios (Low/Medium/High) were generated through calculated annual uncertainty bounds by taking the average of the three policy scenario (FPR, PAC & NDC) outputs and applying a normal distribution with standard deviation across scenarios to derive low (25th percentile), medium (50th percentile), and high (75th percentile) estimates.

Table 3.1.3-1: Step 1 Outputs

Electric Vehicle Type	Estimated Market Penetration in 2050		
	Low	Medium	High
Cars and SUVs	68%	77%	87%
Light and Medium-Duty Trucks	34%	52%	74%
Buses	53%	62%	72%
Heavy Freight Trucks	18%	43%	68%

Assumptions

- Adoption of EVs and Reduction in emissions was calculated using the Virginia Energy Policy Simulator.[6] The assumptions for Virginia Energy Policy Simulator can be found in the model documentation.

[5] Energy Policy Simulator, RMI

[6] Energy Policy Simulator Documentation, RMI.

3.1.4. VTrans Macrotrend # 4: Growth in Shared Mobility

Description: Shared mobility services such as micromobility services (bike sharing, scooter sharing) and ride-hailing (e.g., transportation network companies) continue to expand in scope and services. This trend will show the number of trips that could be accommodated by micromobility and ride-sourcing in 2050.

Drivers:

- Rising costs of private car ownership & fuel/maintenance expenses.[1,2]
- Integration of mobility modes and seamless user interfaces.[3]
- Technological innovations beyond smartphones such as data tools for dynamic pricing, real-time routing and ride matching.[4]
- Younger generations shift in ownership preferences, partly due to automobile affordability.[5]
- Increase in number of workers interested in work hour flexibility or willing to work in the 'gig' economy.[6]

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. Shared mobility has the potential to change travel costs and convenience, and to affect the amount traveled and the modes selected.

[1] The Rising Costs of Owning a Car, The New York Times

[2] The Cost of New Car Ownership Continues to Climb, AAA

[3] Smart Mobility: Trends Transforming Passenger Transport & Mass Transit, VASS Foundation

[4] Revolutionizing Ride Services: The Power of Analytics, Medium

[5] Why are young people driving less? Evidence points to economics, not preferences, Brookings

[6] The Evolution of Platform Gig Work, 2012-2021, Becker Friedman Institute

Data Sources:

- Vehicle Trips: Replica[7]
- Shared Mobility Growth Rates: Uber and Lyft S-1 Filings[8,9] and NACTO[10]
- TNC and Micromobility trip share (baseline): VTtrans Biennial Transportation Survey 2022[11]

Calculations:

1. **Define Analysis Scope –** The analysis was limited to adults (18+) residing in Virginia's urbanized areas (UZA) as defined by the 2020 Census. The in-scope population for the base year was 4,625,523.
2. **Establish Baseline Auto Travel –** Replica travel data was used to compute 2022 trips and vehicle miles traveled (VMT) by geography and aggregated into trip distance bins (under 5 miles and under 30 miles). These estimates were scaled to 2050 using projected population growth factors.
3. **Derive Observed Shared-Mobility Usage –** The VTrans Biennial Transportation Survey provided baseline usage of ride-hailing and micromobility services. Reported availability (Table 3.1.4-1) and weekly frequency bins (Table 3.1.4-2) were converted to daily trip rates and expanded to the in-scope population to establish a current-year baseline.

Table 3.1.4-1: In-scope population and service availability

Trip Purpose	Population (%)	Population (count)
In-scope population (non-work)	100%	4,142,525
TNC available Urban population (non-work travel)	89%	4,142,525
Micromobility available Urban population (non-work travel)	37%	1,722,174
In-scope population (Employed (69%) & Students (5%) - Only)	74%	3,444,347
TNC available Urban population (work/school travel)	88%	3,031,025
Micromobility available Urban population (work/school travel)	35%	1,205,521

Table 3.1.4-2: Current (baseline) utilization of shared-mobility services

Trips per week	TNC				Micromobility			
	Non-work travel		Work travel		Non-work travel		Work travel	
	Population (%)	Population (count)	Population (%)	Population (count)	Population (%)	Population (count)	Population (%)	Population (count)
0	85%	3,521,147	90%	2,727,923	90%	1,549,956	90%	802,877
1.5	11%	455,678	8%	242,482	7%	120,552	7%	62,446
4.5	3%	124,276	2%	60,621	2%	34,443	2%	17,842
8.5	1%	41,425	-	-	-	-	1%	8,921

[7] Replica, Mid-Atlantic, Fall 2022, Typical Thursday

[8] Form S-1 Registration Statement, Uber Technologies, Inc.

[9] Form S-1 Registration Statement, Lyft, Inc.

[10] Shared Mobility Report, NACTO, 2023

[11] Biennial Transportation Survey, VTrans, 2022

4. **Define Switchable Market by Trip Length** – The maximum trip-length market for each mode was determined using published distributions: Zou et al. for micromobility[12] and the Oak Ridge National Laboratory's National Household Travel Survey (NHTS)[13] for ride-hailing. Trips under 5 miles were considered eligible for micromobility; trips under 30 miles were considered eligible for TNC.
5. **Model Adoption Trajectories** – Historical TNC activity (2016–2022) was back-cast by scaling national ride-hailing indices to Virginia. Bass/logistic diffusion curves were fitted to the observed baseline and constrained by the switchable market. Micromobility adoption was modeled using a similar approach to national micromobility benchmarks.
6. **Project Future Trips** – The fitted curves were used to generate Compound annual growth rates (CAGR) used to project daily TNC and Micromobility trips through 2050.
7. **Estimate Auto Trip Displacement** – Mode-switch assumptions were applied to estimate displaced auto trips: 40 percent of TNC trips in the Base scenario.[14] Assumed higher replacement due to AV-robotaxi effects in Medium (60%), and High (80%) scenarios. For micromobility, a constant displacement rate of 37 percent[15] was assumed.
8. **Convert Trips to VMT** – Trip-length distributions (Table 3.1.4-3) were applied to allocate projected trips across distance bins. For TNC, adjustments for occupancy and deadheading were included to compute gross TNC VMT. Micromobility miles were reported separately.

Table 3.1.4-3: Trip distribution by trip length

TNC		Micromobility	
Distance Bins	**Trip distribution**	**Distance Bins**	**Trip distribution**
0–1 mi	9.53%	0–0.5 mi	34.29%
1–2 mi	19.11%	0.5–1 mi	29.89%
2–5 mi	36.04%	1–2 mi	25.49%
5–10 mi	20.94%	2–3 mi	7.03%
10–20 mi	11.01%	3–4 mi	2.64%
20–30 mi	3.37%	4–5 mi	0.66%

9. **Incorporate AV Adoption Effects on TNC** – Survey responses on willingness to use self-driving services[16] were used to construct an "AV wedge" for TNC. A share of current non-users was shifted into user categories, phased in with a centered logistic profile around 2035, consistent with AV macrotrend assumptions.
10. **Develop Scenario Bands** – Scenario bands were produced around the Base path:
    - **TNC:** Base (no AV), Medium (Base + moderate AV effect), High (Base + high AV effect).
    - **Micromobility:** Base path with low/medium/high bounds derived from variation in adoption parameters.

Assumptions :

- Reported weekly usage bins (e.g., 0, 1.5, 4.5, 8.5 trips/week) accurately reflected typical behavior.
- The distribution of non-zero users across frequency bins remained stable over time and applied this observed mix when allocating new adopters into usage bins.
- TNC and micromobility growth constrained by "switchable" private-auto trips defined by distance thresholds (micromobility: < 5 miles; TNC: < 30 miles) and did not allow projected trips to exceed these technical caps.
- Uber & Lyft global trip index provided a suitable proxy for the historical growth pattern of TNC activity in Virginia.
- For TNC AV scenarios, assumed that only current non-users (zero-use respondents) could be converted via willingness to ride self-driving services, and that their eventual usage frequencies followed the existing non-zero user mix.
- Consistent share of TNC and micromobility trips substituted for private-auto trips within the eligible distance bands when estimating displaced auto VMT and did not explicitly model induced demand beyond these substitutions.

[12] Exploratory analysis of real-time e-scooter trip data in Washington, D.C., Zou et al., 2020

[13] Summary of Travel Trends, National Household Travel Survey, 2017

[14] The New Automobility: Lyft, Uber and the Future of American Cities, Schaller Consulting

[15] Mode Replaced by Shared Micromobility, U.S. Dept. of Energy

[16] InteractVTrans | VTrans, Biennial Transportation Survey, VTrans, 2022

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]
- Ease of making a return for an online purchase[3]
- Automation of warehousing[4]

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:

- U.S. Census, Annual Report for Wholesale Trade: 2022[5,6], Quarterly Retail E-Commerce Sales Report[7], Advance Monthly Sales for Retail and Food Services[8], Annual Retail Trade Survey: 2018[9], and County Business Patterns (CBP) Data[10]

[1] National Retail Federation (NRF), 2024 Holiday Retail Sales Outlook found in an October 2024 consumer survey that 57 percent of consumers were planning to make their holiday purchases online, higher than other shopping destinations that include department store, grocery store, discount store, clothing store, small business, electronics store, crafts or fabrics store, outlet store, other specialty store and thrift store.

[2] Businesswire, ShipStation 2024 Survey, found that while 40% of surveyed consumers expect their packages to arrive within 3-5 business days without paying extra for shipping, Gen Z is more willing to pay for shipping for faster deliveries, with 17% of Gen Z expecting delivery within 24 hours.

[3] National Retail Federation (NRF), 2024 Consumer Returns in the Retail Industry found that improving consumers' returns experience tops the list of retailer business goals in 2025 and 84 percent of consumers are more likely to shop with a retailer that offers box-free, label-free returns and immediate refunds. A separate NRF study conducted in October 2024 also found that, on average, retailers' online return rates were 21 percent higher than their overall return rates.

[4] Modern Materials Handling, Peerless Research Group (PRG) and Logistics Management, 2025 Industry Outlook Survey, found that 10 percent of companies are using automatic guided vehicles (AGVs) and autonomous mobile robots (AMRs), 13 percent using robotic solutions like articulating arms or industrial robots

[5] U.S. Census, Annual Report for Wholesale Trade: 2022, U.S. Annual Merchant Wholesalers E-Commerce Sales by Wholesale Trade Industry: 1998-2022.

[6] U.S. Census, Annual Report for Wholesale Trade: 2022, U.S. Annual Merchant Wholesalers Total Sales by Wholesale Trade Industry: 1992-2022.

[7] U.S. Census, Quarterly Retail E-Commerce Sales Report, U.S. Quarterly (Not Seasonally Adjusted) E-Commerce Sales by Retail Trade Industry, 2018-2024.

[8] U.S. Census, Advance Monthly Sales for Retail and Food Services, U.S. Monthly (Not Seasonally Adjusted) Total Sales by Retail Trade Industry, 1992-2024.

[9] U.S. Census, Annual Retail Trade Survey: 2018, U.S. Annual Total and E-commerce Sales by Retail Trade Industry, 1998-2018.

[10] U.S. Census, 2018 County Business Patterns (CBP) Data and 2022 CBP Data, Virginia Statewide Number of Wholesale Trade and Retail Trade Industry Establishments, 2018 and 2022.

- Virginia Department of Taxation Annual Taxable Sales data via Weldon Cooper Center[11]
- U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data[12] and County-Metropolitan Statistical Area (MSA)-CSA Crosswalk[13]
- U.S. Bureau of Economic Analysis (BEA), National Groos Domestic Product (GDP) by Industry[14] and National Employment by Industry[15]
- Woods and Poole Complete Economic and Demographic Data Source (CEDDS)[16]

Calculations:

Estimate E-commerce Market Penetration, Sales and Employment, for the Wholesale Trade or Business-to-Business (B2B) market, for years 2023 and 2050

1. Estimate base year (2023) wholesale trade or B2B e-commerce market penetration rates for the U.S. 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:
   - $Base\ E\text{-}com\ Sales\ \%_i^{US}$: U.S. 2022 wholesale trade or B2B e-commerce sales for NAICS industry *i* gathered from U.S. Census Annual Report for Wholesale Trade[17]
   - $Base\ Total\ Sales_i^{US}$: U.S. 2022 wholesale trade or B2B total sales for NAICS industry *i* gathered from U.S. Census Annual Report for Wholesale Trade[18]
   - *i:* Index for NAICS industries 423 (Durable Goods) and 424 (Nondurable Goods)
   - NOTE: The year 2022 represents the last year of published wholesale trade or B2B data. Historical changes in e-commerce sales for wholesale trade or B2B are gradual and small. Hence, the 2022 data was considered a reasonable proxy for the base year (2023).

2. Apply the base year (2023) U.S. wholesale trade or B2B e-commerce penetration rates by three-digit NAICS industry found in calculation step #1 to estimate weighted average base year (2023) wholesale trade or B2B e-commerce market penetration rate, sales and employment by geography in Virginia.

   $Base\ E\text{-}com\ Sales\ \%_j^{VA} = \sum_i (Base\ E\text{-}com\ Sales\ \%_i^{US} \times Base\ Total\ Sales_{i,j}^{VA}) / \sum_i Base\ Total\ Sales_{i,j}^{VA}$
   $Base\ E\text{-}com\ Sales_j^{VA} = \sum_i B(Base\ E\text{-}com\ Sales\ \%_i^{US} \times Base\ Total\ Sales_{i,j}^{VA})$
   $Base\ E\text{-}com\ Emp_j^{VA} = Base\ E\text{-}com\ Sales\ \%_j^{VA} \times Base\ Total\ Emp_j^{VA}$

   Where:
   - $Base\ E\text{-}com\ Sales\ \%_i^{US}$: Base year (2023) U.S. wholesale trade or B2B e-commerce market penetration rates for NAICS industry *i* estimated in calculation step #1
   - $Base\ Total\ Sales_{i,j}^{VA}$: Base year (2023) wholesale trade or B2B total (taxable) sales by NAICS industry *i* and Virginia geography *j*[19]
   - $Base\ Total\ Emp_j^{VA}$: Base year (2023) wholesale trade or B2B total employment by Virginia geography *j*[20]
   - *j*: index for Virginia geographies that include statewide and metropolitan statistical areas (MSAs) of Blacksburg-Christiansburg-Radford, Charlottesville, Harrisonburg, Lynchburg, Richmond, Roanoke, Staunton-Stuarts Draft, and Virginia parts of Kingsport-Bristol, Virginia Beach-Chesapeake-Norfolk, Washington-Arlington-Alexandria and Winchester.
   - Assumption: The raw data on Virginia's total (taxable) sales data by wholesale trade or B2B industry was available for Virginia counties and cities, which was aggregated to MSAs using a County/City-to-MSA crosswalk assumption.[21]

[11] Virginia Department of Taxation via Weldon Cooper Center, Annual Taxable Sales Data, Annual Taxable Sales by Industry and Locality, 2018-2023.
[12] U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data, Annual Average Employment by Industry and Area, 2023.
[13] U.S. Bureau of Labor Statistics (BLS), County-MSA-CSA Crosswalk, Crosswalk table for reference years of 2024-current.
[14] U.S. Bureau of Economic Analysis (BEA), National GDP by Industry, U.S. Real Gross Output by Industry (in billions of 2017 chain dollars), Annual Totals, 1998-2023.
[15] U.S. Bureau of Economic Analysis (BEA), National Employment by Industry, U.S. Full-Time and Part-Time Employees (in thousands) by Industry, 1998-2023.
[16] Woods and Poole via CDM Smith License, Complete Economic and Demographic Data Source (CEDDS) accessed via CDM Smith's Intranet, Virginia Statewide and Metropolitan Statistical Area (MSA) Wholesale Trade Sector Employment and Retail Trade Sector Sales Forecasts, 1969-2060.
[17] U.S. Census, Annual Report for Wholesale Trade: 2022, U.S. Annual Merchant Wholesalers E-Commerce Sales by Wholesale Trade Industry: 1998-2022.
[18] U.S. Census, Annual Report for Wholesale Trade: 2022, U.S. Annual Merchant Wholesalers Total Sales by Wholesale Trade Industry: 1992-2022.
[19] Virginia Department of Taxation via Weldon Cooper Center, Annual Taxable Sales Data, Annual Taxable Sales by Industry and Locality, 2018-2023.
[20] U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data, Annual Average Employment by Industry and Area, 2023.
[21] U.S. Bureau of Labor Statistics (BLS), County-MSA-CSA Crosswalk, Crosswalk table for reference years of 2024-current.

3. Develop future year (2050) estimates for wholesale trade or B2B e-commerce market penetration rates by three-digit NAICS industry. Use historical (2010-2022) U.S. wholesale trade or B2B e-commerce shares of total sales gathered from U.S. Census Annual Report for Wholesale Trade.

   For NAICS industry 423: *Future E-com Sales* $\%^{US}$ *in year X* = 0.061939 × *ln*(*X*–2001) + 0.137158; $R^2 = 0.84$
   For NAICS industry 424: *Future E-com Sales* $\%^{US}$ *in year X* = 0.095641 × *ln*(*X*–2001) + 0.069213; $R^2 = 0.77$

   Where:
   - *Future E-com Sales* $\%^{US}$ *in year X*: Estimated future U.S. wholesale trade or B2B e-commerce share of total sales in year X for a given NAICS industry
   - *X*: Index for year running from 2023 through 2050
   - Assumption: The national trendline forecasts for e-commerce share of total sales in NAICS industries 423 and 424 were adopted as the medium scenario for Virginia.
   - Assumption: The trendlines did not consider the years of 2020 and 2021 as they were observed to be impacted by a recession due to COVID-19 pandemic. The trendlines used the data only for the years 2010-2019 and 2022.

4. Combine future year (2050) wholesale trade or B2B sector level growth factors for employment by Virginia geography and productivity (real gross output per employee) for U.S. to estimate future year (2050) wholesale trade or B2B sector level total (taxable) sales growth factors by Virginia geography.

   $\textit{Future Total Sales } GF_j^{VA} = \textit{Future Total Emp } GF_j^{VA} \times \textit{Future Productivity } GF^{US}$

   Where:
   - *Future Total Emp* GF_j^{VA}: Future year (2050) employment growth factor (ratio of 2050 value to 2023 value) for wholesale trade or B2B sector by Virginia geography *j* based on the employment forecast scenarios developed under Macrotrend #6
   - *Future Productivity* GF^{US}: Future year (2050) productivity growth factor (ratio of 2050 value to 2023 value) U.S. wholesale trade or B2B sector was developed based on a trendline forecast using historical (2010-2022) U.S. wholesale trade or B2B productivity (real gross output per employee) gathered from U.S. Bureau of Economic Analysis (BEA), Real Gross Output by industry data[22] and Employment by industry data.[23] The equation developed for productivity in future year *X* is as follows:
     $\textit{Productivity in year } X_s^{US} = 119{,}846.97 \times ln(X - 1997) - 16{,}741.30;\ R^2 = 0.90$
   - Assumption: The trendline did not consider the years of 2020 and 2021 as they were observed to be impacted by a recession due to COVID-19 pandemic. The trendline used the data only for the years 2010-2019 and 2022.

5. Apply the future year (2050) wholesale trade or B2B sector level total (taxable) sales growth factors by Virginia geography estimated in calculation step #4 to estimate future year (2050) wholesale trade or B2B total (taxable) sales by NAICS industry *i* and Virginia geography *j*.

   $\textit{Future Total Sales } \%_{i,j}^{VA} = \textit{Future Total Sales } GF_{sj}^{VA} \times \textit{Base Total Sales } \%_{i,j}^{VA}$

   Where:
   - *Future Total Sales* GF_{sj}^{VA}: future year (2050) wholesale trade or B2B sector level total (taxable) sales growth factors by Virginia geography *j*
   - *Base Total Sales* $\%_{i,j}^{VA}$: Base year (2023) wholesale trade or B2B total (taxable) sales by NAICS industry *i* and Virginia geography *j*

[22] U.S. Bureau of Economic Analysis (BEA), National GDP by Industry, U.S. Real Gross Output by Industry (in billions of 2017 chain dollars), Annual Totals, 1998-2023.
[23] U.S. Bureau of Economic Analysis (BEA), National Employment by Industry, U.S. Full-Time and Part-Time Employees (in thousands) by Industry, 1998-2023.

6. Apply the future year (2050) U.S. wholesale trade or B2B e-commerce penetration rates by three-digit NAICS industry estimated in calculation step #3 and future year (2050) employment growth factors found in step #4 to estimate weighted average future year (2050) wholesale trade or B2B e-commerce market penetration rate, sales and employment by geography in Virginia.

   $\textit{Future E-com Sales }\%_j^{US} = \sum_i (\textit{Future E-com Sales }\%_i^{US} \times \textit{Future Total Sales}_{i,j}^{VA}) \,/ \sum_i \textit{Future Total Sales}_{i,j}^{VA}$
   $\textit{Future E-com Sales}_j^{VA} = \sum_i (\textit{Future E-com Sales }\%_i^{US} \times \textit{Future Total Sales}_{i,j}^{VA})$
   $\textit{Future E-com Emp}_i^{VA} = \textit{Future E-com Sales }\%_i^{VA} \times \textit{Future Total Emp GF}_i^{VA} \times \textit{Base E-com Emp}_i^{VA}$

   Where:
   - *Future E-com Sales* $\%_i^{US}$: Future year (2050) U.S. wholesale trade or B2B e-commerce market penetration rates for NAICS industry *i* estimated in calculation step #3
   - *Future Total Sales*$_{i,j}^{VA}$: Future year (2050) wholesale trade or B2B total (taxable) sales by NAICS industry *i* and Virginia geography *j* estimated in calculation step #5
   - *Future Total Emp GF*$_j^{VA}$: Future year (2050) employment growth factor (ratio of 2050 value to 2023 value) for wholesale trade or B2B sector by Virginia geography *j* gathered in calculation step #4
   - *Base Total Emp*$_i^{VA}$: Base year (2023) wholesale trade or B2B total employment by Virginia geography *j* gathered in calculation step #2

Estimate E-commerce Market Penetration, Sales and Employment, for the Retail Trade or Business-to-Consumer (B2C) market, for years 2023 and 2050

7. Estimate base year (2023) retail trade or B2C e-commerce market penetration rates for the U.S. by three-digit NAICS industry.

   $\textit{Base E-com Sales }\%_i^{US} = \textit{Base E-Com Sales}_i^{US} / \textit{Base Total Sales}_i^{US}$

   Where:
   - *Base E-Com Sales*$_i^{US}$: U.S. 2022-2024 (3-year) average retail trade or B2C e-commerce sales for NAICS industry *i* gathered from U.S. Census Quarterly Retail E-Commerce Sales Report[24]
   - *Base Total Sales*$_i^{US}$: U.S. 2022-2024 (3-year) average retail trade or B2C total sales for NAICS industry *i* gathered from U.S. Census Advance Monthly Sales for Retail and Food Services[25]
   - *i*: Index for NAICS industries 441 (Motor Vehicle and Parts Dealers), 442 (Furniture and Home Furnishings Stores), 443 (Electronics and Appliance Stores), 444 (Building Material and Garden Equipment and Supplies Dealers), 445 (Food and Beverage Retailers), 446 (Health and Personal Care Stores), 447 & 453 (Miscellaneous Store Retailers including Gasoline Stations), 448 (Clothing and Clothing Accessories Stores), 451 (Sporting Goods, Hobby, Book, and Music Stores), 452 (General Merchandise Stores), and 454 (Nonstore Retailers)

8. Adjust the base year (2023) retail trade or B2C e-commerce market penetration rates for the U.S. by three-digit NAICS industry by re-allocating NAICS 454 (nonstore retailers) to NAICS 441 through 453 (which are more precise in terms of the sale commodities) using U.S. BLS data and methodology.[26]

   $$\begin{aligned}&\textit{Adj.Base E-com Sales }\%_i^{US}\\&\quad= \textit{Base E-com Sales }\%_i^{US} \times \textit{Base Total Sales}_i^{US}\\&\quad+ \textit{Base E-com Sales }\%_{\textit{NAICS 454}}^{US} \times \textit{Base Total Sales}_{454}^{US} \times \textit{Alloc}_{\textit{454 to i}}^{US}\end{aligned}$$

[24] U.S. Census, Quarterly Retail E-Commerce Sales Report, U.S. Quarterly (Not Seasonally Adjusted) E-Commerce Sales by Retail Trade Industry, 2018-2024.

[25] U.S. Census, Advance Monthly Sales for Retail and Food Services, U.S. Monthly (Not Seasonally Adjusted) Total Sales by Retail Trade Industry, 1992-2024.

[26] Shane Haley and Kennedy Keller, "The NAICS 2022 update and its effect on BLS employment estimates in the retail trade sector," Monthly Labor Review, U.S. Bureau of Labor Statistics, September 2023, https://doi.org/10.21916/mlr.2023.19, Chart 1. Ratio of employment reclassified from NAICS 2017 industries into new NAICS 2022 retail industries.

Where:

- *Base E-com Sales* $\%_i^{US}$: Base year (2023) U.S. retail trade or B2C e-commerce market penetration rates for NAICS industry *i* estimated in calculation step #7
- $Alloc_{454\ to\ i}^{US}$: U.S. BLS' suggested fractions of NAICS 4541 (Electronic Shopping and Mail-Order Houses) and NAICS 45439 (Other Direct Selling Establishments) employment allocated to NAICS industry *i*, which are further weighted and combined using U.S. employment data for NAICS 4541 and NAICS 45439
- NOTE: The employment distributions for the 2021 U.S. employment data (NAICS 2017 industry classification-based) after calculations to re-allocate NAICS 454 to NAICS 441 through 453 were compared against the 2023 U.S. employment data (NAICS 2022 industry classification-based, which already comes with a re-classified NAICS 454). The distributions matched closely. Based on this verification, this method was extended and applied to U.S. total sales and e-commerce sales to re-allocate total and e-commerce sales of NAICS 454 to NAICS 441 through 453 and estimate the adjusted e-commerce shares. As the e-commerce share for NAICS 454 is 48.4 percent (i.e., high), the re-allocation resulted in higher e-commerce shares for NAICS 441 through 453.

9. Apply the adjusted base year (2023) U.S. retail trade or B2C e-commerce penetration rates by three-digit NAICS industry found in calculation step #8 to estimate weighted average base year (2023) retail trade or B2C e-commerce market penetration rate, sales and employment by geography in Virginia.

$$Base\ E\text{-}com\ Sales\ \%_j^{VA} = \textstyle\sum_i (Adj.Base\ E\text{-}com\ Sales\ \%_i^{US} \times Base\ Total\ Sales_{ij}^{VA}) / \sum_i Base\ Total\ Sales_{ij}^{VA}$$
$$Base\ E\text{-}com\ Sales_j^{VA} = \textstyle\sum_i (Adj.Base\ E\text{-}com\ Sales\ \%_i^{US} \times Base\ Total\ Sales_{ij}^{VA}$$
$$Base\ E''\text{-}com\ Emp_i^{VA} = Adj.Base\ E\text{-}com\ Sales\ \%_i^{VA} \times Base\ Total\ Emp_i^{VA}$$

Where:

- *Adj.Base E-com Sales* $\%_i^{VA}$: Base year (2023) adjusted U.S. retail trade or B2C e-commerce market penetration rates for NAICS industry *i* estimated in calculation step #8
- *Base Total* $Sales_{ij}^{VA}$: Base year (2023) retail trade or B2C total (taxable) sales by NAICS industry *i* and Virginia geography *j*[27]
- *Base Total* Emp_j^{VA}: Base year (2023) retail trade or B2C total employment by Virginia geography *j*[28]
- *j*: index for Virginia geographies that include statewide and metropolitan statistical areas (MSAs) of Blacksburg-Christiansburg-Radford, Charlottesville, Harrisonburg, Lynchburg, Richmond, Roanoke, Staunton-Stuarts Draft, and Virginia parts of Kingsport-Bristol, Virginia Beach-Chesapeake-Norfolk, Washington-Arlington-Alexandria and Winchester.
- Assumption: The raw data on Virginia's total (taxable) sales data by retail trade or B2C industry was available for Virginia counties and cities, which was aggregated to MSAs using a County/City-to-MSA crosswalk assumption.[29]

10. Develop future year (2050) estimates for retail trade or B2C e-commerce market penetration rates by three-digit NAICS industry. Use historical (2010-2022) U.S. retail trade or B2C e-commerce shares of total sales gathered from U.S. Census Quarterly Retail E-Commerce Sales Report[30], Advance Monthly Sales for Retail and Food Services[3], and Annual Retail Trade Survey: 2018.[32]
For retail trade or B2C sector:

$$Future\ E\text{-}com\ Sales\ \%^{US}\ in\ year\ X = 2.2\% + 0.006950 \times X – 2001 – 0.021855;\ R^2 = 0.99$$

Where:

- *Future E-com Sales* $\%^{US}$ *in year X*: Estimated future U.S. retail trade or B2C e-commerce share of total sales in year *X* for a given NAICS industry
- 2.2%: COVID-19 pandemic correction for a noticeable shift in retail trade or B2C e-commerce related consumer behavior pre-COVID-19 pandemic, i.e., year 2019 or earlier versus post-COVID-19 pandemic, i.e., year 2022 or later. The remainder of the trendline expression represents the trendline drawn based on 2010-2019 data.
- *X*: Index for year running from 2022 through 2050

[27] Virginia Department of Taxation via Weldon Cooper Center, Annual Taxable Sales Data, Annual Taxable Sales by Industry and Locality, 2018-2023.

[28] U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data, Annual Average Employment by Industry and Area, 2023.

[29] U.S. Bureau of Labor Statistics (BLS), County-MSA-CSA Crosswalk, Crosswalk table for reference years of 2024-current.

[30] U.S. Census, Quarterly Retail E-Commerce Sales Report, U.S. Quarterly (Not Seasonally Adjusted) E-Commerce Sales by Retail Trade Industry, 2018-2024.

[31] U.S. Census, Advance Monthly Sales for Retail and Food Services, U.S. Monthly (Not Seasonally Adjusted) Total Sales by Retail Trade Industry, 1992-2024.

[32] U.S. Census, Annual Retail Trade Survey: 2018, U.S. Annual Total and E-commerce Sales by Retail Trade Industry, 1998-2018.

- Assumption: The trendlines did not consider the years of 2020 and 2021 as they were observed to be impacted by a recession due to COVID-19 pandemic. The trendlines used the data only for the years 2010-2019, and used 2022-2024 data versus estimate average difference for upward correction of the e-commerce share in future years of 2025 through 2050.
- Assumption: The estimated 2050 national forecast retail trade or B2C e-commerce share of 34.0 percent based on the above equation is 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.

11. Through a study of state and national retail trade data and research articles, gather future year (2050) medium scenario (most likely) retail trade or B2C e-commerce market penetration assumptions by 3-digit NAICS industry, i.e., *Future E-com Sales* $\%_i^{US}$. These are done as adjustments to the base year (2023) retail trade or B2C e-commerce shares for U.S. by NAICS industry, i.e., *Base E-com Sales* $\%_i^{US}$. The key findings and assumptions are as follows:
    - **U.S. Census County Business Patterns (CBP) Data[33]**: Based on recent trends (2018-2022) in the Commonwealth of Virginia, there is a reduction in retail trade establishments of 14.5 percent of 448 (Clothing and Clothing Accessories Stores), 14.1 percent of 443 (Electronics and Appliance Stores), and 10.7 percent of 442 (Furniture and Home Furnishings Stores). There is 17.4 percent increase in 454 (Nonstore Retailers), 7.4 percent increase in 445 (Food and Beverage Retailers), and 6.5 percent increase in 452 (General Merchandise Stores).
    - **Large retail chain bankruptcies[34] and store closures[35, 36]:** Nationally, there have been several retail trade related bankruptcies filed between 2020 and 2024 that include national chains in 446 (Health and Personal Care Stores, e.g., L'Occitane, Rite Aid) 447 (Miscellaneous Store Retailers, e.g., Bed, Bath & Beyond, Party City), 448 (Clothing and Clothing Accessories Stores, e.g., Ascena Retail, Christopher & Banks, Express), 451 (Sporting Goods, Hobby, Book, and Music Stores, e.g., JOANN), and 452 (General Merchandise Stores, e.g, J. C. Penny, Nieman Marcus, Belk, 99 Cents). In addition to bankruptcy filings, there are several reported store closures in 2024 under 446 (Health and Personal Care Stores, e.g., CVS – 600 stores closed), 448 (Clothing and Clothing Accessories Stores, e.g., Foot Locker – 118 stores closed, some Macy's and Kohl's stores also closed) and 452 (General Merchandise Stores, e.g, 7-Eleven - 500 stores and Family Dollar - 718 stores closed).
    - **Industry specific assumptions:** Assume slow e-commerce growth (rounding up to the nearest 5%) for 444 (Building Material and Garden Equipment and Supplies Dealers) on the basis that the products except janitorial, sanitation and hardware supplies are less suitable to online sales.[37] In contrast, assume high e-commerce growth (rounding up to the nearest 5% and an added 20% online sale increase) for 442 (Furniture and Home Furnishings Stores), 446 (Health and Personal Care Stores), and 448 (Clothing and Clothing Accessories Stores) due to the ongoing trends of reducing number of retail store establishments, several large retail chain bankruptcies and store closures. Despite the ongoing trend of decreasing number of retail store establishments for the retail industry of 443 (Electronics and Appliance Stores), assume moderate e-commerce growth (rounding up to the nearest 5% and an added 10% online sale increase), due to the reason that NAICS 443 has already reached a mature e-commerce market penetration rate of 70.9 percent in 2023. Assume moderate e-commerce growth (rounding up to the nearest 5% and an added 10% online sale increase) for all remaining retail trade industries, and there is some replacement of the closing stores.

12. Gather future year (2050) retail trade or B2C sector level total (taxable) sales and employment growth factors by Virginia geography, i.e., *Future Total Sales* GF_i^{VA} and *Future Total Emp* GF_i^{VA} from the employment forecast scenarios developed under Macrotrend #6.

[33] U.S. Census, 2018 County Business Patterns (CBP) Data and 2022 CBP Data, Virginia Statewide Number of Wholesale Trade and Retail Trade Industry Establishments, 2018 and 2022.

[34] Cornerstone, Trends in Large Corporate Bankruptcy and Financial Distress, Mid-Year Reports, 2020-2024.

[35] https://www.aarp.org/money/personal-finance/retail-stores-closing/ (accessed on March 17, 2025)

[36] https://www.forbes.com/sites/pamdanziger/2025/01/30/retail-apocalypse-well-over-twice-as-many-stores-will-close--as-open-in-2025/ (accessed on March 17, 2025)

[37] https://distributionstrategy.com/wp-content/uploads/2023/03/DSG-2023-State-of-eCommerce-in-Distribution.pdf (accessed on March 17, 2025)

13. Apply the future year (2050) retail trade or B2C sector level total (taxable) sales growth factors by Virginia geography estimated in calculation step #12 to estimate future year (2050) retail trade or B2C total (taxable) sales by NAICS industry *i* and Virginia geography *j*.

    $Future\ Total\ Sales\ \%_{i,j}^{VA} = Future\ Total\ Sales\ GF_{s,j}^{VA} \times Base\ Total\ Sales\ \%_{i,j}^{VA}$

    Where:

    - $Future\ Total\ Sales\ GF_{s,j}^{VA}$: future year (2050) retail trade or B2C sector level total (taxable) sales growth factors by Virginia geography *j*
    - $Base\ Total\ Sales\ \%_{i,j}^{VA}$: Base year (2023) retail trade or B2C total (taxable) sales by NAICS industry *i* and Virginia geography *j*

14. Apply the future year (2050) U.S. retail trade or B2C e-commerce penetration rates by three-digit NAICS industry assumed in step #11 and future year (2050) employment growth factors found in step #12 to estimate weighted average future year (2050) retail trade or B2C e-commerce market penetration rate, sales and employment by geography in Virginia.

    $Future\ E\text{-}com\ Sales\ \%_j^{VA} = \sum_i (Future\ E\text{-}com\ Sales\ \%_i^{US} \times Future\ Total\ Sales_{i,j}^{VA}) \ / \ \sum_i Future\ Total\ Sales_{i,j}^{VA}$
    $Future\ E\text{-}com\ Sales_j^{VA} = \sum_i (Future\ E\text{-}com\ Sales\ \%_i^{US} \times Future\ Total\ Sales_{i,j}^{VA})$
    $Future\ E\text{-}com\ Emp_j^{VA} = Future\ E\text{-}com\ Sales\ \%_j^{VA} \times Future\ Total\ Emp\ GF_j^{VA} \times Base\ E\text{-}com\ Emp_j^{VA}$

    Where:

- $Future\ E\text{-}com\ Sales\ \%_i^{US}$: Future year (2050) U.S. retail trade or B2C e-commerce market penetration rates for NAICS industry *i* estimated in calculation step #11
- $Future\ Total\ Sales_{i,j}^{VA}$: Future year (2050) retail trade or B2C total (taxable) sales by NAICS industry *i* and Virginia geography *j* estimated in calculation step #13
- $Future\ Total\ Emp\ GF_j^{VA}$: Future year (2050) employment growth factor (ratio of 2050 value to 2023 value) for retail trade or B2C sector by Virginia geography *j* gathered in calculation step #12
- $Base\ Total\ Emp_j^{VA}$: Base year (2023) retail trade or B2C total employment by Virginia geography *j* gathered in calculation step #9

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 projections, goods movement, location of services and skills requirements. All of these directly have transportation and economic impacts.

[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.

Data Sources:

- U.S. Bureau of Labor Statistics (BLS), Virginia Geography Quarterly Census of Employment & Wages (QCEW) Data,[4] National Industry-Specific Occupational Mix,[5] National Occupational Projections,[6] U.S. Employment and Output Projections,[7] U.S. Productivity Data,[8] County-Metropolitan Statistical Area (MSA)-CSA Crosswalk[9]
- Woods and Poole Complete Economic and Demographic Data Source (CEDDS)[10]
- Virginia Department of Taxation Annual Taxable Sales data via Weldon Cooper Center[11]
- U.S. Bureau of Economic Analysis (BEA), National Gross Domestic Product (GDP) and Gross Output by Industry,[12] National Employment by Industry,[13] State GDP by Industry[14]
- O*NET® 29.3 Database, SOC and Work Activities, Work Context and Abilities[15]
- Data and research findings on the effects of increase in industrial robots sales and use[16,17,18,19]
- Data and research findings on the effects of increase in generative artificial intelligence (Gen AI) development and use[20,21,22,23,24]
- Data and research findings on the uses and growth of 3D printing[25,26,27]
- Industry sales growth forecasts for industrial robots and 3D printing[28,29,30,31,32]

[4] U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data, Annual Average Employment by Industry and Area, 2023.

[5] U.S. Bureau of Labor Statistics (BLS), National Industry-Specific Occupation Mix, May 2023.

[6] U.S. Bureau of Labor Statistics (BLS), National Occupational Projections, 2023-2033.

[7] U.S. Bureau of Labor Statistics (BLS), Employment and Output Projections, National Annual Average Employment and Output Projections by Industry, 2014 and 2023-2033.

[8] U.S. Bureau of Labor Statistics (BLS), Productivity Data, National Labor Productivity and Costs, Total Factor Productivity, Information Processing Equipment Costs, and Intellectual Property Products Costs for Major Sectors and Major Industries, 1987-2023.

[9] U.S. Bureau of Labor Statistics (BLS), County-MSA-CSA Crosswalk, Crosswalk table for reference years of 2024-current.

[10] Woods and Poole via CDM Smith License, Complete Economic and Demographic Data Source (CEDDS) accessed via CDM Smith's Intranet, Virginia Statewide and Metropolitan Statistical Area (MSA) Wholesale Trade Sector Employment and Retail Trade Sector Sales Forecasts, 1969-2060.

[11] Virginia Department of Taxation via Weldon Cooper Center, Annual Taxable Sales Data, Annual Taxable Sales by Industry and Locality, 2018-2023.

[12] U.S. Bureau of Economic Analysis (BEA), National GDP by Industry and National Gross Output by Industry, Annual Totals, 1998-2023.

[13] U.S. Bureau of Economic Analysis (BEA), National Employment by Industry, U.S. Full-Time and Part-Time Employees (in thousands) by Industry, 1998-2023.

[14] U.S. Bureau of Economic Analysis (BEA), State GDP by Industry, Annual Total, 2023.

[15] O*NET® 29.3 Database, SOC and Work Activities, Work Context and Abilities.

[16] Acemoglu, D. and Restrepo, P., 2017, Robots and Jobs: Evidence from US Labor Markets. NBER, Working Paper 23285.

[17] U.S. Department of Commerce, International Trade Administration, 2020, Robots and the Economy - The Role of Automation in Driving Productivity Growth.

[18] International Federation of Robotics (IFR), Stock of U.S. Industrial Robots, 2013-2023.

[19] Labor Market Information (LMI), 2025. Automation exposure score methodology.

[20] MIT, 2023. Workforce Effects of Automation and AI - Shaping the Future of Work Policy Memo.

[21] Abrahams, Scott and Levy, Frank S., From San Francisco to Savannah? The Downstream Effects of Generative AI, Social Science Research Network (SSRN).

[22] Felten, E. W. and Raj, M., and Seamans, R., 2023, Occupational Heterogeneity in Exposure to Generative AI, Social Science Research Network (SSRN).

[23] Acemoglu, D. and Restrepo, P., 2022, Tasks, Automation, and the Rise in U.S. Wage Inequality, Econometrica, Vol. 90, No. 5, 1973–2016.

[24] Babina, T., Fedyk, A., He, A., and Hodson, J., 2024, Artificial intelligence, firm growth, and product innovation, Journal of Financial Economics, Volume 151, 103745, ISSN 0304-405X.

[25] Machine Design Article, 2019, The State of Online 3D Printing, by Alkaios Bournias Varotsis.

[26] Omar Jumaah, Doctoral Thesis, 2018, A Study on 3D Printing and its Effects on the Future of Transportation, The Center for Advanced Infrastructure and Transportation (CAIT).

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

[28] Grandview Research, 2024, U.S. Industrial Robotics Market Size, Share & Trends Analysis Report By Application, By End-use, By Robot Type, By Payload Capacity, By Component, And Segment Forecasts, 2024 – 2030.

[29] Statzon, 2023, Industrial Robot Market Size Report, 2023-2033.

[30] Precedence Research, 3D Printers Market Size, Share, and Trends 2025 to 2034, Available at: (last accessed on April 24, 2025)

[31] PROTOLABS, 3D Printing Trend Report 2024, 2040.

[32] 3D Printing Industry Article titled 3D Printing industry hits new high at $20 billion according to Wohlers Report 2024, Deeper Insight from Terry Wohlers," by Alex Tyrer Jones dated April 4, 2024.

Calculations:

Gather base year (2023) employment data for all sectors and develop employment growth scenarios for future year (2050)

1. Gather base year (2023) annual average number of establishments and employment by industry and Virginia geography for all sectors.[33] Impute missing 2023 regional employment data for the sectors using regional establishments data and statewide employment per establishment factors.

   $Base\ Emp_{i,j}^{VA} = Base\ Est_{i,j}^{VA} \times (Base\ Total\ Emp_{i}^{VA} / Base\ Total\ Est_{i}^{VA})$

   Where:

   - $Base\ Est_{i,j}^{VA}$: Base year (2023) establishments by NAICS industry *i* and Virginia geography *j*
   - $Base\ Total\ Emp_{i}^{VA}$: Base year (2023) total employment by NAICS industry *i* in Virginia
   - $Base\ Total\ Est_{i}^{VA}$: Base year (2023) total establishments by NAICS industry *i* in Virginia
   - *i*: Index for NAICS sectors 11 (agriculture, forestry, fishing, and hunting), 21 (mining, quarrying, and oil and gas extraction), 22 (utilities), 23 (construction), 31-33 (manufacturing), 42 (wholesale trade), 44-45 (retail trade), 48-49 (transportation and warehousing), 51 (information), 52 (finance and insurance), 53 (real estate and rental and leasing), 54 (professional, scientific, and technical services), 55 (management of companies and enterprises), 56 (administrative and support and waste management and remediation services), 61 (educational services), 62 (health care and social assistance), 71 (arts, entertainment, and recreation), 72 (accommodation and food Services), 81 (other services (except public administration)), and 99 (federal, state, and local government)
   - *j*: index for Virginia geographies that include:
     a. Statewide
     b. Metropolitan Statistical Areas (MSAs) of Blacksburg-Christiansburg-Radford, Charlottesville, Harrisonburg, Lynchburg, Richmond, Roanoke, Staunton-Stuarts Draft, and Virginia parts of Kingsport-Bristol, Virginia Beach-Chesapeake-Norfolk, Washington-Arlington-Alexandria and Winchester
     a. Planning District Commissions (PDCs) of Accomack-Northampton, Central Shenandoah, Central Virginia, Commonwealth Regional Council, Crater, Cumberland Plateau, George Washington, Hampton Roads, Lenowisco, Middle Peninsula, Mount Rogers, New River Valley, Northern Neck, Northern Shenandoah Valley, Northern Virginia, Rappahannock-Rapidan, Richmond Regional, Roanoke Valley-Alleghany, Southside, Thomas Jefferson and West Piedmont
     b. VDOT construction districts of Bristol, Culpeper, Fredericksburg, Hampton Roads, Lynchburg, Northern Virginia, Richmond, Salem and Staunton

2. For NAICS sector 31-33 (manufacturing sector) only, prepare 2023 regional manufacturing sector employment and statewide manufacturing industry employment control totals. Estimate adjusted 2023 employment by manufacturing industry and Virginia geography using Fratar (iterative) method to distribute the employment at regional and manufacturing industry levels to simultaneously match the two control totals. This corrects any errors introduced by the data imputation in Step #1.

   $Adj\ Base\ Emp_{i,j}^{VA} = Fratar\ Method\ applied\ to\ Base\ Emp_{i,j}^{VA}$
   With $Base\ Total\ Emp_{i}^{VA}$ *and* $Base\ Total\ Emp_{i}^{VA}$ as control totals

   Where:
   $Base\ Total\ Emp_{i}^{VA}$: Base year (2023) total employment in manufacturing sector by Virginia geography *j*
   $Base\ Total\ Emp_{i}^{VA}$A: Base year (2023) total employment by manufacturing industry *i* in Virginia
   i: Index for three-digit NAICS industries of 311-312 (food and beverage and tobacco products), 313-314 (textile mills and textile product mills), 315-316 (apparel and leather and applied products), 321 (wood products), 322 (paper and paper products), 323 (printing and related support activities), 324 (petroleum and coal products), 325 (chemicals), 326 (plastics and rubber products), 327 (nonmetallic mineral products), 331 (primary metals), 332 (fabricated metal products), 333 (machinery), 334 (computer and electronic products), 335 (electrical equipment and appliances), 336 (transportation equipment), 337 (furniture and related products), and 339 (miscellaneous manufacturing)

[33] U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data, Annual Average Employment by Industry and Area, 2023.

3. Develop three employment growth scenarios using three different methodologies for future year (2050) employment growth factor (ratio of 2050 value to 2023 value) by Virginia geography *j* for all sectors as follows:
   a. **High (W&P Emp.) Scenario:** Apply Woods and Poole employment forecasts[34] by using all sectors total employment growth factors by Virginia geography and statewide employment growth by industry as control values. This scenario sets the statewide total employment growth factor at the highest value of 1.39 and results in a statewide total employment estimate of 5.24 million persons. The total employment growth factors set at lower Virginia geography levels under this scenario are shown in Table 3.1.6-1 on the next page. The growth factors for statewide employment by industry are initially set also directly based on Woods and Poole employment forecasts. However, after the application of these growth factors to the 2023 statewide employment by industry and adding the 2050 statewide employment estimates across all industries, the total employment comes out as 5.53 million persons, which differs from 5.24 million persons. To conserve the 5.24 million persons total, the statewide employment growth factors by industry are relatively downward adjusted by a factor of 0.95. The statewide employment growth factors used at the industry level under this scenario are shown in Table 3.1.6-2. The final step of deriving employment growth factors by Virginia geography and industry is explained in Step #4.
   b. **Medium (W&P Emp. Adj. to Wrk. Age Pop.) Scenario:** This scenario replaces the Woods and Poole employment forecasts at Virginia geography level with Woods and Poole working age (18-65 years) population forecasts[35] at Virginia geography level as control values. This scenario sets the statewide total employment growth factor at the medium value of 1.16 and results in a statewide total employment estimate of 4.37 million persons. The total employment growth factors set at lower Virginia geography levels under this scenario are shown in Table 3.1.6-1 on the next page. It is noted that the growth factor of 1.16 seen in the working age (18-65 years) population is lower than the overall (all ages total) population growth factor of 1.22 based on Woods & Poole. An adjustment factor is applied to the statewide employment growth factors by industry in a similar manner as the High Scenario, but the adjustment factor is lower at 0.79 due to the lower statewide total employment. The statewide employment growth factors used at the industry level under this scenario are shown in 3.1.6-2. The final step of deriving employment growth factors by Virginia geography and industry is explained in Step #4.
   c. **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario:** This scenario uses the same estimation steps as the Medium Scenario. In addition, this scenario uses three sub-methodologies to adjust the statewide total employment growth factor to 1.15 and statewide total employment to 4.34 million persons, respectively, as follows:
      - **Growth of the use of industrial robots and associated employment loss and productivity increase effects** (see Step #6)
      - **Gen AI development and use growth and associated geographical displacement effects on employment** (see Step #7)
      - **Gen AI development and use growth and associated increasing share of AI-skilled occupations** (see Step #8)

      Under this scenario, the total employment growth factors derived at lower Virginia geography levels are shown in Table 3.1.6-1 on the next page and the statewide employment growth factors derived at the industry level are shown in Table 3.1.6-2.

[34]Woods and Poole via CDM Smith License, Complete Economic and Demographic Data Source (CEDDS) accessed via CDM Smith's Intranet, Virginia Statewide and County Level, Employment Forecasts, 1969-2060.

[35]Woods and Poole via CDM Smith License, Complete Economic and Demographic Data Source (CEDDS) accessed via CDM Smith's Intranet, Virginia Statewide and County Level, Working Age (18-65 years) Forecasts, 1969-2060.

Table 3.1.6-1: Future Year (2050) Virginia Geography Employment Growth Factors by Employment Growth Scenario

		Forecast Employment (2050)			Employment Growth Factor (2050)		
	Base Year Emp. (2023)	2050 High (W&P Emp.) Scenario	2050 Medium (W&P Emp Adj. to Wrk. Age Pop.) Scenario	2050 Low (W&P Emp Adj. to Wrk. Age Pop. + AI/Auto.) Scenario	2050 High (W&P Emp.) Scenario	2050 Medium (W&P Emp Adj. to Wrk. Age Pop.) Scenario	2050 Low (W&P Emp Adj. to Wrk. Age Pop. + AI/Auto.) Scenario
STATEWIDE							
Total	3,783,695	5,244,437	4,374,538	4,335,507	1.39	1.16	1.15
VDOT CONSTRUCTION DISTRICTS							
Bristol	99,969	108,584	90,984	89,003	1.09	0.91	0.89
Culpeper	172,736	238,329	207,264	205,803	1.38	1.20	1.19
Fredericksburg	156,600	258,620	204,969	203,973	1.65	1.31	1.30
Hampton Roads	750,871	933,446	779,202	794,719	1.24	1.04	1.06
Lynchburg	148,081	176,788	152,898	149,620	1.19	1.03	1.01
Northern Virginia	1,285,568	2,031,389	1,652,439	1,630,290	1.58	1.29	1.27
Richmond	659,487	876,598	744,646	731,918	1.33	1.13	1.11
Salem	275,852	319,515	283,682	277,334	1.16	1.03	1.01
Staunton	234,531	301,168	258,454	252,847	1.28	1.10	1.08
PLANNING DISTRICT COMMISSIONS							
Accomack-Northampton	15,999	17,871	15,113	14,655	1.12	0.94	0.92
Central Shenandoah	130,226	169,441	138,515	135,257	1.30	1.06	1.04
Central Virginia	100,290	128,392	111,235	108,964	1.28	1.11	1.09
Commonwealth Regional Council	24,439	29,895	24,629	24,359	1.22	1.01	1.00
Crater	60,102	71,386	61,712	60,821	1.19	1.03	1.01
Cumberland Plateau	25,994	27,893	22,025	21,787	1.07	0.85	0.84
George Washington	118,148	212,723	163,698	163,157	1.80	1.39	1.38
Hampton Roads	724,013	902,978	753,324	769,496	1.25	1.04	1.06
Lenowisco	20,731	23,562	18,891	18,676	1.14	0.91	0.90
Middle Peninsula	26,150	30,895	28,051	27,827	1.18	1.07	1.06
Mount Rogers	62,573	67,518	59,649	57,720	1.08	0.95	0.92
New River Valley	72,676	84,254	77,185	74,765	1.16	1.06	1.03
Northern Neck	12,301	13,826	12,964	12,782	1.12	1.05	1.04
Northern Shenandoah	98,165	125,649	114,235	111,975	1.28	1.16	1.14
Northern Virginia	1,285,568	2,031,175	1,650,263	1,628,105	1.58	1.28	1.27
Rappahannock-Rapidan	53,327	69,925	63,278	62,563	1.31	1.19	1.17
Richmond Regional	585,985	792,172	674,419	662,638	1.35	1.15	1.13
Roanoke Valley-Alleghany	152,563	175,572	155,823	153,394	1.15	1.02	1.01
Southside	25,237	26,654	23,046	22,617	1.06	0.91	0.90
Thomas Jefferson	123,881	174,381	148,502	147,643	1.41	1.20	1.19
West Piedmont	65,327	68,275	57,981	56,306	1.05	0.89	0.86

	Base Year Emp. (2023)	Forecast Employment (2050) 2050 High (W&P Emp.) Scenario	2050 Medium (W&P Emp Adj. to Wrk. Age Pop.) Scenario	2050 Low (W&P Emp Adj. to Wrk. Age Pop. + AI/Auto.) Scenario	Employment Growth Factor (2050) 2050 High (W&P Emp.) Scenario	2050 Medium (W&P Emp Adj. to Wrk. Age Pop.) Scenario	2050 Low (W&P Emp Adj. to Wrk. Age Pop. + AI/Auto.) Scenario
METROPOLITAN STATISTICAL AREAS							
Blacksburg-Christiansburg-Radford	72,676	84,061	77,647	75,464	1.16	1.07	1.04
Charlottesville	114,858	160,593	138,607	138,289	1.40	1.21	1.20
Harrisonburg	65,066	90,633	74,632	73,735	1.39	1.15	1.13
Kingsport-Bristol	32,265	34,522	30,504	29,945	1.07	0.95	0.93
Lynchburg	100,290	128,098	111,900	110,273	1.28	1.12	1.10
Richmond	647,023	862,788	739,782	729,273	1.33	1.14	1.13
Roanoke	146,420	169,092	151,611	149,204	1.15	1.04	1.02
Staunton-Stuarts Draft	50,223	61,709	49,795	49,439	1.23	0.99	0.98
Virginia Beach-Chesapeake-Norfolk	731,969	913,825	770,163	780,313	1.25	1.05	1.07
Washington-Arlington-Alexandria	1,449,656	2,078,130	1,723,549	1,701,414	1.43	1.19	1.17
Winchester	61,213	79,932	73,486	72,808	1.31	1.20	1.19
Not a MSA	312,036	581,054	432,862	425,350	1.86	1.39	1.36

Table 3.1.6-2: Future Year (2050) Industry Employment Growth Factors by Employment Growth Scenario

	Base Year Emp. (2023)	Forecast Employment (2050) 2050 High (W&P Emp) Scenario	2050 Medium (W&P Emp Adj. to Wrk. Age Pop.) Scenario	2050 Low (W&P Emp Adj. to Wrk. Age Pop. + AI/Auto.) Scenario	Employment Growth Factor (2050) 2050 High (W&P Emp.) Scenario	2050 Medium (W&P Emp Adj. to Wrk. Age Pop.) Scenario	2050 Low (W&P Emp Adj. to Wrk. Age Pop. + AI/Auto.) Scenario
STATEWIDE							
Total	3,783,695	5,244,437	4,374,538	4,335,507	1.39	1.16	1.15
INDUSTRY SECTOR							
11 - Agriculture, Forestry, Fishing and Hunting	12,817	11,689	9,750	9,747	0.91	0.76	0.76
21 - Mining, Quarrying, and Oil and Gas Extraction	5,560	4,991	4,163	4,160	0.90	0.75	0.75
22 - Utilities	18,701	18,325	15,285	15,282	0.98	0.82	0.82
23 - Construction	223,477	221,049	184,383	184,360	0.99	0.83	0.82
31-33 - Manufacturing	254,870	227,345	189,635	150,983	0.89	0.74	0.59
42 - Wholesale Trade	113,967	108,863	90,805	90,805	0.96	0.80	0.80
44-45 - Retail Trade	399,551	406,264	338,877	338,877	1.02	0.85	0.85
48-49 - Transportation and Warehousing	171,460	208,528	173,939	173,939	1.22	1.01	1.01
51 - Information	75,130	61,712	51,476	51,476	0.82	0.69	0.69
52 - Finance and Insurance	147,427	205,221	171,181	171,181	1.39	1.16	1.16
53 - Real Estate and Rental and Leasing	59,758	85,311	71,161	71,161	1.43	1.19	1.19

	Base Year Emp. (2023)	Forecast Employment (2050)			Employment Growth Factor (2050)		
		2050 High (W&P Emp) Scenario	2050 Medium (W&P Emp Adj. to Wrk. Age Pop.) Scenario	2050 Low (W&P Emp Adj. to Wrk. Age Pop. + AI/Auto.) Scenario	2050 High (W&P Emp.) Scenario	2050 Medium (W&P Emp Adj. to Wrk. Age Pop.) Scenario	2050 Low (W&P Emp Adj. to Wrk. Age Pop. + AI/Auto.) Scenario
54 - Professional, Scientific, and Technical Services	474,713	811,095	676,558	676,558	1.71	1.43	1.43
55 - Management of Companies and Enterprises	87,179	90,329	75,346	75,346	1.04	0.86	0.86
56 - Administrative and Support and Waste Management and Remediation Services	256,377	365,981	305,276	305,276	1.43	1.19	1.19
61 - Educational Services	368,527	686,005	572,217	571,870	1.86	1.55	1.55
62 - Health Care and Social Assistance	529,878	852,208	710,852	710,852	1.61	1.34	1.34
71 - Arts, Entertainment, and Recreation	79,646	124,486	103,837	103,837	1.56	1.30	1.30
72 - Accommodation and Food Services	344,789	547,756	456,899	456,899	1.59	1.33	1.33
81 - Other Services (except Public Administration)	136,593	180,906	150,899	150,899	1.32	1.10	1.10
99 - Federal, State, and Local Government	23,275	26,373	21,999	21,999	1.13	0.95	0.95

4. For all NAICS sectors and given employment growth scenario, prepare 2050 regional total employment and statewide industry sector employment control totals. Estimate adjusted 2050 employment by industry sector and Virginia geography using Fratar (iterative) method to distribute the employment at regional and industry levels to simultaneously match the two control totals. Use the statewide industry shares for all Virginia geographies as a seed (initial) value for employment by Virginia geography and industry. Repeat this step for all employment growth scenarios. The control totals and thus calculations will be identical for **Medium (W&P Emp. Adj. to Wrk. Age Pop.) Scenario** and **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario**, and different for **High (W&P Emp.) Scenario**.

   $Adj\ Future\ Emp_{i,j}^{VA} = Fratar\ Method\ applied\ to\ Future\ Emp_{i,j}^{VA}$
   With $Future\ Total\ Emp_{j}^{VA}$ and $Future\ Total\ Emp_{i}^{VA}$ as control totals

   Where:
   - $Future\ Total\ Emp_{j}^{VA}$: Future year (2050) total employment across all sectors by Virginia geography *j* under the given employment growth scenario
   - $Future\ Total\ Emp_{i}^{VA}$: Future year (2050) total employment by industry sector *i* in Virginia under the given employment growth scenario.

5. Gather base year (2023) National Industry-Specific Occupational Mix[36] and project 2033 industry-specific occupations mix by applying the 2023-2033 National Occupational Projections.[37] Assume the projected 2033 industry-specific occupations mix to be applicable to 2050 **High (W&P Emp.) Scenario** and **Medium (W&P Emp. Adj. to Wrk. Age Pop.) Scenario**. Also, set the projected 2033 industry-specific occupations mix as the initial (starter) values for 2050 L**ow (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario**.

   If the employment growth scenario is either **High (W&P Emp.) Scenario** or **Medium (W&P Emp. Adj. to Wrk. Age Pop.) Scenario**, this step concludes the employment growth calculations, proceed to the productivity growth calculations in Step #9. However, if the employment growth scenario is **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario**, continue to the next step (i.e., Step #6).

[36] U.S. Bureau of Labor Statistics (BLS), National Industry-Specific Occupation Mix, May 2023.

[37] U.S. Bureau of Labor Statistics (BLS), National Occupational Projections, 2023-2033.

6. **Sub-methodology for Industrial robots use growth and associated employment loss and productivity increase effects:** Applicable only to **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario**
   a. **Definition:** *Industrial Robot* is an automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or fixed to a mobile platform for use in automation applications in an industrial environment. (ISO 8373:2021).
   b. Identify U.S. industrial robot market penetration by industry, in terms of 2023 robot density (robots per 1,000 employees) by combining Acemoglu et al's 2004-2014 U.S. industrial robot density data,[38] U.S. BLS employment by industry for the U.S. in 2014 and 2023,[39] 2014-2023 IFR stock of industrial robots in the U.S.[40] (see Table 3.1.6-3 for estimates).
   c. Use 50 percent of the average of two short-term growth rates as the long-term growth rate for industrial robot market in the U.S., i.e., 50 percent of 5.4 percent (compound annualized growth rate or CAGR over 2024-2030)[41] and 11.0 percent (CAGR over 2023-2029),[42] which equals 4.0 percent. Apply the long-term growth rate on the 2023 robot density by industry to estimate 2050 robot density by industry.
   d. Estimate future year (2050) increase in the number of robots by industry in Virginia by multiplying 2023 and 2050 statewide employment by industry outputs in Step #4 with 2023 and 2050 estimates for robot density by industry and taking a difference.

Table 3.1.6-3: Base Year (2023) and Future Year (2050) Industrial Robot Density Estimates

NAICS Industry Code	NAICS Industry	U.S. Industrial Robot Density (robots per 1,000 workers)	
		2023	2050
11	Agriculture, Forestry, Fishing and Hunting	0.054	0.157
21	Mining, Quarrying, and Oil and Gas Extraction	0.132	0.380
22	Utilities	0.040	0.115
23	Construction	0.023	0.066
61	Educational Services	0.082	0.235
311	Food manufacturing	7.894	22.760
312	Beverages and tobacco products	5.779	16.662
313	Textile mills	0.100	0.288
314	Textile product mills	0.090	0.259
315	Apparel	0.113	0.326
316	Leather and allied products	0.076	0.219
321	Wood products	0.318	0.916
322	Paper and paper products	0.170	0.491
323	Printing and related support activities	15.126	43.614
324	Petroleum and coal products	15.126	43.615
325	Chemicals	13.239	38.173
326	Plastics and rubber products	13.578	39.150
327	Nonmetallic mineral products	0.920	2.653
331	Primary metals	11.449	33.012

[38]Acemoglu, D. and Restrepo, P., 2017, Robots and Jobs: Evidence from US Labor Markets. NBER, Working Paper 23285.

[39]U.S. Bureau of Labor Statistics (BLS), Employment and Output Projections, National Annual Average Employment and Output Projections by Industry, 2014 and 2023-2033.

[40]International Federation of Robotics (IFR), Stock of U.S. Industrial Robots, 2013-2023.

[41]Grandview Research, 2024, U.S. Industrial Robotics Market Size, Share & Trends Analysis Report By Application, By End-use, By Robot Type, By Payload Capacity, By Component, And Segment Forecasts, 2024 – 2030.

[42]Statzon, 2023, Industrial Robot Market Size Report, 2023-2033.

NAICS Industry Code	NAICS Industry	U.S. Industrial Robot Density (robots per 1,000 workers)	
		2023	2050
332	Fabricated metal products	12.466	35.945
333	Machinery	3.531	10.181
334	Computer and electronic products	18.766	54.108
335	Electrical equipment and appliances	17.904	51.623
336	Transportation equipment	155.272	447.705
337	Furniture and related products	0.373	1.075
339	Miscellaneous manufacturing	11.582	33.395

e. Apply Acemoglu et al's elasticity factor of 3.3 job losses per 1 robot added[43] between 2023 and 2050, to estimate statewide job losses to robotic automation by industry by 2050. The sub-methodology estimated **a statewide loss of 39,031 jobs to automation due to increasing use of industrial robots**. Allocate the statewide job losses to industries and Virginia geographies in proportion of the employment in each industry and Virginia geography. Thus, estimate $Future\ Emp\ Loss_{i,j}^{VA,Auto}$, where *i* is the index for industry and *j* is the index for Virginia geography. Estimate the second adjusted future year (2050) employment estimate for 2050 L**ow (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario** using the first adjusted future year (2050) employment estimate for 2050 **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario** in Step #4 and $Future\ Emp\ Loss_{i,j}^{VA,Auto}$ as follows:

$$Second\ Adj\ Future\ Emp_{i,j}^{VA,Low} = Adj\ Future\ Emp_{i,j}^{VA,Low} + Future\ Emp\ Loss_{i,j}^{VA,Auto}$$

f. Determine the likelihood of the automation related job loss to fall within a standard occupational classification (SOC) code. For this, apply LMI's methodology[44] to O*NET 29.3 Database[45] and establish automation exposure rating (1 lowest, 10 highest) by SOC code.

g. Assume job loss allocation rules of up to 50 percent loss in employment in the SOC occupations with automation exposure rating (AER) range of 8-10, followed by up to 25 percent loss in the AER range of 5-7, and no employment loss in the AER range of 1-4. Table 3.1.6-4 is showing the SOC occupations with 5 or above automation exposure rating.

Take the example of the manufacturing industry sector, the total job loss in this sector was estimated as 38,652 jobs. In this sector, under 2050 **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario**, prior to consideration of automation and AI effects, there are 52,350 jobs expected in occupations with AER range of 8-10, 98,735 jobs expected in occupations with AER range of 5-7, and 38,550 jobs expected in occupations with AER range of 1-4. Applying the rules, the job loss in occupations with AER range of 8-10 was limited to 50 percent of 52,350 jobs, i.e., 26,175 jobs. The remaining job loss, 38,652 minus 26,175, equals 12,477 jobs are estimated in the occupations in the AER range of 5-7. 12,477 jobs form 12.6 percent (less than 25 percent) of 98,735 jobs. No job losses are computed in occupations with AER range of 1-4. Total jobs in the manufacturing sector at the end of Step #4 was 189,635; after the calculations accounting for the automation effects in this step, this dropped by 38,652 jobs, to 150,983 jobs.

h. Adjust the initial (starter) industry-specific occupations mix under the 2050 **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario** based on the job loss allocations to SOC occupations in the previous sub-step to estimate a new 2050 industry-specific occupational mix after accounting for the automation effects.

i. Increase in automation due to increasing use of industrial robots also has a productivity growth effect which is discussed in Step #10. For now, proceed to the next step, i.e., Step #7.

[43]Acemoglu, D. and Restrepo, P., 2017, Robots and Jobs: Evidence from US Labor Markets. NBER, Working Paper 23285.

[44]Labor Market Information (LMI), 2025. Automation exposure score methodology.

[45]O*NET® 29.3 Database, SOC and Work Activities, Work Context and Abilities.

7. **Sub-methodology for Gen AI development and use growth and associated geographical displacement effects on employment:** Applicable only to **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario**
   a. **Definition:** *Generative Artificial Intelligence (Generative AI or GenAI)* is a subfield of artificial intelligence that uses generative models to produce text, images, videos, or other forms of data.
   b. Following a similar logic to a MIT's workforce policy memo,[46] identify 44 SOC occupations that have high exposure to Gen AI and automation, which are identified using a combination of criteria as follows: Felten et al's Gen AI occupation exposure score (AIOE) > 1.0 and LMI methodology-based automation exposure rating (AER) > = 5. The list of occupations meeting these criteria are shown in Table 3.1.6-5.

Table 3.1.6-4: Standard Occupational Classification (SOC) Occupations with High Level of Gen AI and Automation Exposure

SOC Code	Title	AIOE >= 1	AER >= 5
11-9121	Natural Sciences Managers	1.241	3
13-1031	Claims Adjusters, Examiners, and Investigators	1.106	6
13-2031	Budget Analysts	1.3	6
13-2071	Credit Counselors	1.355	5
13-2081	Tax Examiners and Collectors, and Revenue Agents	1.253	5
13-2082	Tax Preparers	1.144	5
19-1042	Medical Scientists, Except Epidemiologists	1.167	5
23-1012	Judicial Law Clerks	1.513	6
23-1021	Administrative Law Judges, Adjudicators, and Hearing Officers	1.547	5
23-2011	Paralegals and Legal Assistants	1.333	6
23-2093	Title Examiners, Abstractors, and Searchers	1.384	6
27-3042	Technical Writers	1.317	6
27-3043	Writers and Authors	1.17	4
27-3091	Interpreters and Translators	1.352	5
31-9094	Medical Transcriptionists	1.196	7
41-3021	Insurance Sales Agents	1.427	5
41-3041	Travel Agents	1.278	5
41-4012	Sales Representatives, Wholesale and Manufacturing, Except Technical and Scientific Products	1.039	5
41-9041	Telemarketers	1.926	6
43-2011	Switchboard Operators, Including Answering Service	1.244	7
43-2021	Telephone Operators	1.412	7
43-3011	Bill and Account Collectors	1.27	5
43-3021	Billing and Posting Clerks	1.136	7
43-3051	Payroll and Timekeeping Clerks	1.155	7
43-3061	Procurement Clerks	1.59	5
43-4011	Brokerage Clerks	1.026	7
43-4021	Correspondence Clerks	1.184	6
43-4031	Court, Municipal, and License Clerks	1.336	6
43-4041	Credit Authorizers, Checkers, and Clerks	1.546	5
43-4051	Customer Service Representatives	1.076	6
43-4061	Eligibility Interviewers, Government Programs	1.417	6
43-4111	Interviewers, Except Eligibility and Loan	1.449	5

SOC Code	Title	AIOE >= 1	AER >= 5
43-4131	Loan Interviewers and Clerks	1.274	5
43-4141	New Accounts Clerks	1.201	6
43-4161	Human Resources Assistants, Except Payroll and Timekeeping	1.481	5
43-4171	Receptionists and Information Clerks	1.033	6
43-5011	Cargo and Freight Agents	1.255	6
43-5032	Dispatchers, Except Police, Fire, and Ambulance	1.128	6
43-6011	Executive Secretaries and Executive Administrative Assistants	1.106	5
43-6012	Legal Secretaries	1.149	5
43-6013	Medical Secretaries	1.298	6
43-6014	Secretaries and Administrative Assistants, Except Legal, Medical, and Executive	1.254	6
43-9041	Insurance Claims and Policy Processing Clerks	1.257	7
43-9081	Proofreaders and Copy Markers	1.436	8

c. As per Acemoglu et al,[47] task displacement due to automation historically (1980-2016) has ranged between no change to 25 percent for various demographic groups. This analysis assumed a mid-value displacement effect of up to 12.5 percent of the jobs only in high Gen AI and automation exposure occupations. The share of high Gen AI and automation exposure occupations varies by industry as shown in Table 3.1.6-6.

For example, in Washington-Arlington-Alexandria MSA, there are 145,714 jobs in high Gen AI and automation exposure occupations (the 44 occupations identified in Table 3.1.6-4). Of these, 12.5 percent, i.e., 18,214 jobs are expected to be displaced to another geography.

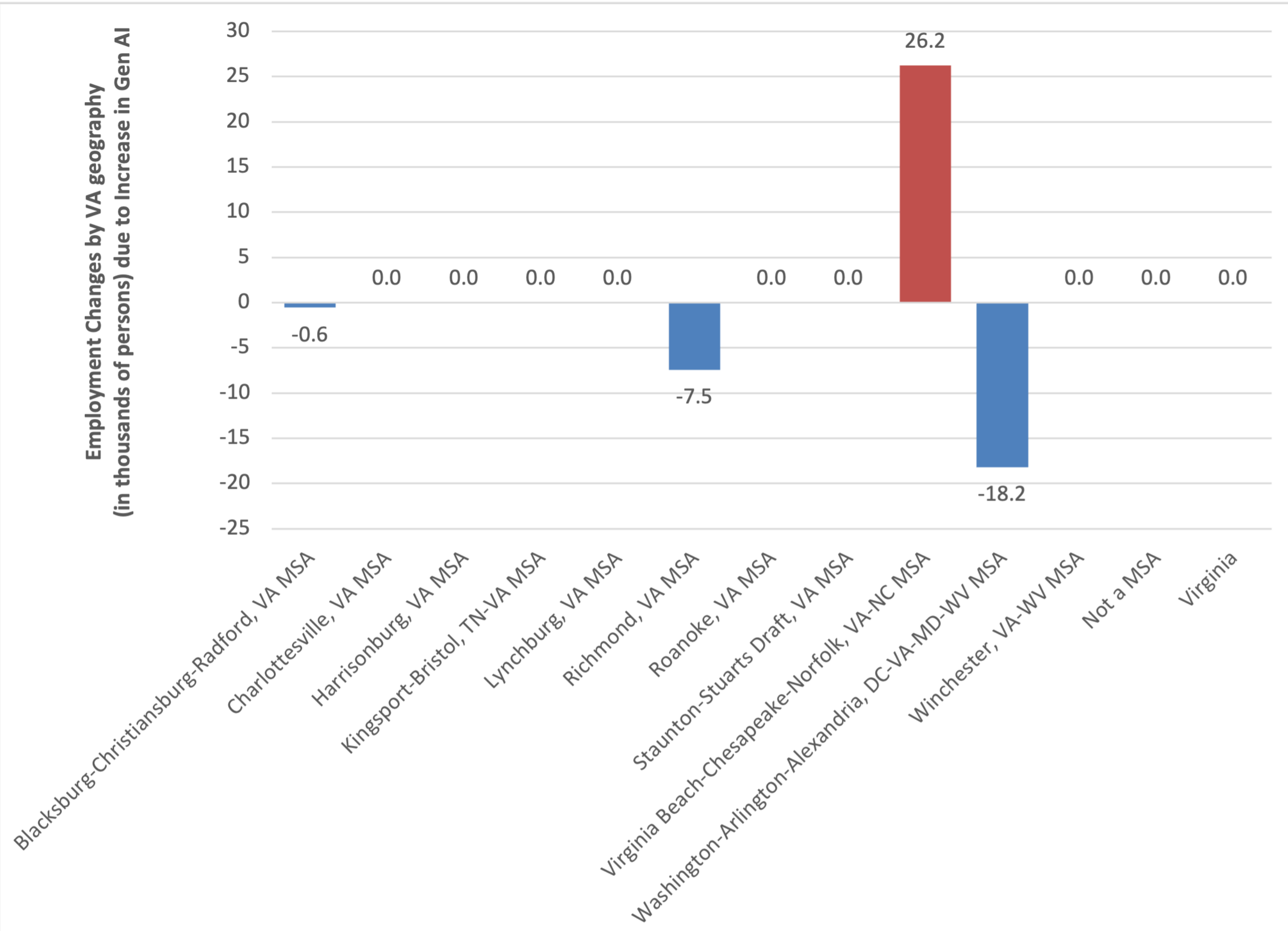
Table 3.1.6-5: Future Year (2050) Share of High Gen AI and Automation Exposure Jobs by Industry

NAICS Industry Sector	Share of Jobs in "Table 3.1.6-4" Occupations out of Total Jobs
11 - Agriculture, Forestry, Fishing and Hunting	1.7%
21 - Mining, Quarrying, and Oil and Gas Extraction	2.7%
22 - Utilities	7.3%
23 - Construction	3.2%
31-33 - Manufacturing	3.8%
42 - Wholesale Trade	18.4%
44-45 - Retail Trade	4.6%
48-49 - Transportation and Warehousing	5.3%
51 - Information	6.9%
52 - Finance and Insurance	29.0%
53 - Real Estate and Rental and Leasing	7.2%
54 - Professional, Scientific, and Technical Services	12.6%
55 - Management of Companies and Enterprises	12.0%
56 - Administrative and Support and Waste Management and Remediation Services	10.1%
61 - Educational Services	4.5%
62 - Health Care and Social Assistance	7.2%
71 - Arts, Entertainment, and Recreation	5.8%
72 - Accommodation and Food Services	0.4%
81 - Other Services (except Public Administration)	7.1%
99 - Federal, State, and Local Government	9.3%

a. Based Abrahams et al,[48] job displacements were considered from only high Gen AI exposure MSAs of Washington-Arlington-Alexandria, Richmond and Blacksburg-Christiansburg-Radford. Also, based on Abrahams et al and newly gathered socioeconomic datasets,[49,50,51] Virginia Beach-Chesapeake-Norfolk MSA was identified to have suitable characteristics for receiving the jobs displaced due to growth in development and use of Gen AI. The suitable characteristics of Virginia Beach-Chesapeake-Norfolk MSA are as follows: lower Gen AI exposure risk, above 410,000 population, college share among adults of higher than 35 percent, median home price of less than $225 per square foot. Figure 3.1.6-1 shows the anticipated future year (2050) job displacement impacts across Virginia geographies, with the highest increase of 26,225 jobs to Virginia Beach-Chesapeake-Norfolk MSA, but no net increase or decline over the state. Thus, estimate future year (2050) job displacement impact due to Gen AI, *Future Emp Geog Shift*$_{i,j}^{VA,AI}$, where *i* is the index for industry and *j* is the index for Virginia geography. Estimate the third adjusted future year (2050) employment estimate for 2050 **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario** using the second adjusted future year (2050) employment estimate for 2050 **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario** in Step #4 and *Future Emp Geog Shift*$_{i,j}^{VA,AI}$ as follows:

Third Adj Future Emp$_{i,j}^{VA,Low}$ = Second Adj Future Emp$_{i,j}^{VA,Low}$ + Future Emp Geog Shift$_{i,j}^{VA,AI}$

Figure 3.1.6-1. Anticipated Future Year (2050) Job Displacement Impacts due to Increase in Development and Use of Gen AI Applications



[47] Acemoglu, D. and Restrepo, P., 2022, Tasks, Automation, and the Rise in U.S. Wage Inequality, Econometrica, Vol. 90, No. 5, 1973–2016.

[48] Abrahams, Scott and Levy, Frank S., From San Francisco to Savannah? The Downstream Effects of Generative AI, Social Science Research Network (SSRN).

[49] U.S. Census, 2025, MSA July 1, 2024 Population Estimate.

[50] Virginia Realtors, 2023, Educational Attainment by Metro Area.

[51] Federal Reserve Bank of St. Louis, July 2025, Median Listing Price per Square Foot in Metropolitan Areas.

b. Begin with the industry-specific occupations mix under the 2050 **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario** that accounts for the automation related job loss impacts and adjust the mix based on the Gen AI related job displacement impacts taking one Virginia geography at a time. Given the job displacement impacted only 4 MSAs, the mix change calculations are performed for these 4 Virginia geographies. The mix was kept undisturbed and the same for all other MSAs and Non-MSA. As a result, 5 individual industry-specific occupational mixes are derived at the end of this step. These five occupational mixes are assigned to the planning district commissions (PDCs) and VDOT construction districts (CDs) based on their overlap with the affected MSAs. Table 3.1.6-7 shows the MSA level industry-specific occupational mix table type and the PDC and CD associated with each industry-specific occupational mix table.

c. Proceed to the next step, i.e., Step #8.

Table 3.1.6-6: MSAs with Industry-Specific Occupation Mix Tables and Assignments to PDCs and CDs

MSA with Individual Industry-Specific Occupational Mix Table	Assigned PDC	Assigned CD
Washington-Arlington-Alexandria	Northern Virginia	Northern Virginia
Richmond	Richmond Regional	Richmond
Blacksburg-Christiansburg-Radford	New River Valley	Salem
Virginia Beach-Chesapeake-Norfolk	Hampton Roads	Hampton Roads
All Other MSAs including Non-MSA	All Other PDCs	All Other CDs

8. **Sub-methodology for Gen AI development and use growth and associated increasing share of AI-skilled occupations:** Applicable only to **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario**
   a. Definition: *AI-Skilled Jobs* are emerging set of jobs with titles such as those shown in Table 3.1.6-8 and skills such as those shown in Table 3.1.6-9.

Table 3.1.6-7: AI-Skilled Job Titles

AI-Skilled Job Titles
Research Engineer - Natural Language Processing
Computer Vision & Image Processing Researcher
Algorithm Developer
Senior Autonomous Vehicle Localization Software Engineer
Speech Recognition Scientist
Data Scientist
Data Mining Engineer
Big Data Engineer
Big Data Senior Data Scientist
Data Scientist

Table 3.1.6-8: AI-Skilled Job Skills

AI Skills		
Artificial Intelligence	TensorFlow	Maximum Entropy Classifier
Computer Vision	Vowpal	Hidden Markov Model (HMM)
Machine Learning	Convolutional Neural Network (CNN)	Pybrain
Natural Language Processing	Jung Framework	Computational Linguistics
ND4J (software)	OpenNLP	Naive Bayes
Kernel Methods	Natural Language Toolkit (NLTK)	H2O (software)
Microsoft Cognitive Toolkit	Unsupervised Learning	Expectation-Maximization (EM) Algorithm
Xgboost	Dlib	WEKA
Sentiment Classification	Scikit-learn	Clustering Algorithms
Long Short-Term Memory (LSTM)	Latent Semantic Analysis	Matrix Factorization
Libsvm	Latent Dirichlet Allocation	Object Recognition
Semi-Supervised Learning	Stochastic Gradient Descent (SGD)	Classification Algorithms
Recurrent Neural Network (RNN)	Gradient boosting	Information Extraction
Word2Vec	Dimensionality Reduction	Image Recognition
MXNet	Deep Learning	Bayesian Networks
Caffe Deep Learning Framework	DBSCAN (Density-Based Spatial Clustering of Applications with Noise)	Supervised Learning (Machine Learning)
Autoencoders	AI ChatBot	OpenCV
MLPACK (C++ library)	Recommender Systems	K-Means
Keras	Random Forests	Sentiment Analysis / Opinion Mining
Theano	Deeplearning4j	Machine Translation (MT)
Torch (Machine Learning)	Support Vector Machines (SVM)	Neural Networks
Wabbit	Unstructured Information Management Architecture	
Boosting (Machine Learning)	Apache UIMA	

b. Using Babina et al[52] analysis of Burning Glass job postings, and 2010 and 2016 estimates, derive base year (2023) and future year (2050) market penetration of emerging AI-skilled jobs by industry using linear extrapolation (see Table 3.1.6-10). Call these $Base\ AIJobsPerc_i$ and $Future\ AIJobsPerc_i$.

Table 3.1.6-9: Future Year (2050) Share of High Gen AI and Automation Exposure Jobs by Industry

NAICS Industry Sector	Share of AI-Skilled Jobs out of Total Jobs			
	2010 (approx. mid-year) Share	2016 (approx. mid-year) Share	2023 (Estimated) Share	2050 (Estimated) Share
11 - Agriculture, Forestry, Fishing and Hunting	0.00%	0.00%	0.00%	0.00%
21 - Mining, Quarrying, and Oil and Gas Extraction	0.10%	0.35%	0.64%	1.77%
22 - Utilities	0.10%	0.20%	0.32%	0.77%
23 - Construction	0.10%	0.10%	0.10%	0.10%
31-33 - Manufacturing	0.10%	0.60%	1.18%	3.43%
42 - Wholesale Trade	0.10%	0.10%	0.10%	0.10%
44-45 - Retail Trade	0.10%	0.25%	0.43%	1.10%
48-49 - Transportation and Warehousing	0.10%	0.25%	0.43%	1.10%
51 - Information	0.57%	1.68%	2.98%	7.97%
52 - Finance and Insurance	0.10%	0.60%	1.18%	3.43%
53 - Real Estate and Rental and Leasing	0.10%	0.15%	0.21%	0.43%
54 - Professional, Scientific, and Technical Services	0.25%	1.30%	2.53%	7.25%
55 - Management of Companies and Enterprises	0.10%	0.10%	0.10%	0.10%
56 - Administrative and Support and Waste Management and Remediation Services	0.10%	0.25%	0.43%	1.10%
61 - Educational Services	0.10%	0.10%	0.10%	0.10%
62 - Health Care and Social Assistance	0.10%	0.10%	0.10%	0.10%
71 - Arts, Entertainment, and Recreation	0.10%	0.10%	0.10%	0.10%
72 - Accommodation and Food Services	0.10%	0.10%	0.10%	0.10%
81 - Other Services (except Public Administration)	0.10%	0.10%	0.10%	0.10%
99 - Federal, State, and Local Government	0.10%	0.10%	0.10%	0.10%

c. Estimate the increase in jobs in AI-skilled occupations between 2023 and 2050 using:
$Future\ AI\ Emp\ Shift_{i,j}^{VA,AI}$
$= Third\ Adj\ Future\ Emp_{i,j}^{VA,Low} \times Future\ AIJobsPerc_i$
$- Base\ Emp_{i,j}^{VA,Low} \times Base\ AIJobsPerc_i$

d. Assign the increase in AI-skilled jobs to the closely related SOC 15-1221 - Computer and Information Research Scientists. Assign the same quantity of decrease in non-AI-skilled jobs to all other SOC occupations proportionate to their shares in the 5 individual industry-specific occupational mixes developed in the previous step. So, the net change in employment by Virginia geography and industry due to increase in AI-skilled jobs would be zero. In other words, $Final\ Adj\ Future\ Emp_{i,j}^{VA,Low} = Third\ Adj\ Future\ Emp_{i,j}^{VA,Low}$

e. Unlike industrial robots related automation, based on Babina et al,[53] the effect of an increase in development and use of Gen AI on productivity cannot be determined with a statistical significance, in other words, is uncertain. So, this step concludes the effects of increasing development and use of Gen AI.

[52] Babina, T., Fedyk, A., He, A., and Hodson, J., 2024, Artificial intelligence, firm growth, and product innovation, Journal of Financial Economics, Volume 151, 103745, ISSN 0304-405X.

[53] Babina, T., Fedyk, A., He, A., and Hodson, J., 2024, Artificial intelligence, firm growth, and product innovation, Journal of Financial Economics, Volume 151, 103745, ISSN 0304-405X.

Quantify the Productivity and Sales Growth in Goods Movement Dependent Sectors, for years 2023 and 2050

9. Gather the sales estimates for NAICS 42 (wholesale trade) and NAICS 44-45 (retail trade) for years 2023 and 2050 developed for Macrotrend #5.
10. Gather base year (2023) Virginia GDP contributions for goods movement dependent sectors, except wholesale trade and retail trade industries. Apply National Gross Output to GDP ratios by industry sector to the State GDP values to estimate state gross output for goods movement dependent sectors.

    $Base\ Output_i^{VA} = Base\ GDP_i^{VA} \times (Base\ Output_i^{US} / Base\ GDP_i^{US})$

    Where:
    - $Base\ GDP_i^{VA}$: base year (2023) Real GDP (in chained 2017$) for Virginia[54]
    - $Base\ Output_i^{US}$: base year (2023) Real Gross Output (in chained 2017$) for U.S.[55]
    - $Base\ GDP_i^{US}$: base year (2023) Real GDP (in chained 2017$) for U.S.[56]
    - i: Index for NAICS goods movement dependent sectors of 11 (agriculture, forestry, fishing, and hunting), 21 (mining, quarrying, and oil and gas extraction), 22 (utilities), 23 (construction), 31-33 (manufacturing), 48-49 (transportation and warehousing)

11. Gather base year (2023) total (taxable) sales by industry and Virginia geography for all goods movement dependent sectors. Adjust the statewide total (taxable) sales to the estimated base year (2023) output by industry sector for Virginia estimated in Step #10, and apply the same adjustment factor for all Virginia geographies and industries within the industry sector.

    $Adj.Base\ Sales_{i,j}^{VA} = Base\ Sales_{i,j}^{VA} \times Base\ Output_i^{VA} / \sum_j Base\ Sales_{i,j}^{VA}$

    Where:
    - $Base\ Sales_{i,j}^{VA}$: base year (2023) taxable sales by industry and Virginia geography[57]

12. Impute missing 2023 regional sales data for goods movement dependent sectors except wholesale trade and retail trade industries using regional employment estimates and statewide sales per employment factors. Also, adjust the 2023 regional total sales estimates for an industry by evaluating the ratio of 2023 regional productivity (total sales per employee estimate) to the 2023 state productivity (total sales estimate per employee) for that industry and capping this to a minimum value of 0.25. This reduces inconsistencies between the sources of employment and sales data. After all missing data imputations and capping adjustments are completed, for a given industry sector, the sum of sales across all Virginia geographies and industries may no longer match the state gross output for that industry sector. So, perform a final proportionate upward or downward adjustment to the 2023 sales in those Virginia geographies that did not require a minimum capping adjustment until the sum of sales matches the state gross output.

    $Base\ Sales_{i,j}^{VA} = Base\ Emp_{i,j}^{VA} \times (Base\ Output_i^{VA} / \sum_j Base\ Emp_{i,j}^{VA})$

    Where:
    - $Base\ Emp_{i,j}^{VA}$: Base year (2023) employment estimates by NAICS industry i and Virginia geography j

13. For NAICS sectors 11, 21, 22, 23, 31-33 and 48-49, add base year (2023) sales estimates from Step #9 and 12 to estimate base year (2023) sales for goods movement dependent sectors total.

    $Base\ GM\ Sales_j^{VA} = \sum_{i \in GM} Base\ Sales_{i,j}^{VA}$

    Where:
    - GM: Goods movement dependent NAICS sectors 11, 21, 22, 23, 31-33, 42, 44-45 and 48-49

[54] U.S. Bureau of Economic Analysis (BEA), State GDP by Industry, Annual Total, 2023.

[55] U.S. Bureau of Economic Analysis (BEA), National GDP by Industry and National Gross Output by Industry, Annual Totals, 1998-2023.

[56] U.S. Bureau of Economic Analysis (BEA), National GDP by Industry and National Gross Output by Industry, Annual Totals, 1998-2023.

[57] Virginia Department of Taxation via Weldon Cooper Center, Annual Taxable Sales Data, Annual Taxable Sales by Industry and Locality, 2018-2023.

14. For NAICS sectors 11, 21, 22, 23 and 48-49, estimate future year (2050) sales growth factors by Virginia geography by combining future year (2050) employment growth factors by Virginia geography gathered in Steps #1-8 and productivity (real gross output per employee) growth factors. For MSA geographies, assume the productivity growth factors to be based on Woods and Poole's future year (2050) earnings per employee growth factors. For non-MSA geography, assume growth factor of 1.0 in productivity for these sectors.

    $Future\ Sales\ GF_{i,j}^{VA} = Future\ Emp\ GF_{i,j}^{VA} \times Future\ Productivity\ GF_{i}^{US}$

    Where:
    - $Future\ Emp\ GF_{i,j}^{VA}$: Future year (2050) employment growth factor (ratio of 2050 value to 2023 value) by Virginia geography *j* for NAICS sectors 11, 21, 22, 23 and 48-49 based on employment growth scenarios developed in Steps #1-8
    - $Future\ Productivity\ GF_{i}^{US}$: Future year (2050) productivity growth factor (ratio of 2050 value to 2023 value) for U.S. and for NAICS sectors 11, 21, 22, 23 and 48-49, if MSA geography, use Woods & Poole earnings per employee growth factors, else use 1.0

15. For NAICS sector 31-33 only, a more detailed sales growth forecasting approach was used. At three-digit NAICS industry level, sales growth factors, i.e. $Future\ Sales\ GF_{i,j}^{VA}$, are a blend of the following:
    - Assumption: A minimum value of employment growth factor, i.e., $Future\ Emp\ GF_{i,j}^{VA}$. In other words, the minimum productivity (real gross output per employee) growth factor is assumed as 1.0.
    - Average of the growth factor based on an output forecasting model (ratio of 2050 output estimate to 2023 output estimate) developed by CDM Smith using historical (2000-2023) U.S. Productivity Data[58] and the growth factor directly based on U.S. BLS output growth projections (2023-2033) for U.S.,[59] both by three-digit NAICS manufacturing industry
        - The output forecasting model is a linear statistical model that uses natural logarithm of 5-year average real sectoral output (in millions of 2023 dollars) as dependent variable and natural logarithm of 5-year average employment (in thousands of jobs), natural logarithm of 5-year average labor productivity index (2019-2023 average=100), natural logarithm of 5-year average capital productivity index (2019-2023 average=100) as independent variables. Fitted parameters for the output forecasting model are shown in Table 3.1.6-11. For base year (2023) and future year (2050), the output forecasting model was evaluated. For this, employment values in thousands of jobs in 2023 and 2050 by Virginia geography and manufacturing industry were used as inputs. Base year (2023) value of 100 and future year (2050) trendline forecasts based on recent historical (2018-2023) were used as inputs for labor and capital productivity indices.
        - Table 3.1.6-12 shows the growth factors based on U.S. BLS projections; these vary only by the manufacturing industry.

Table 3.1.6-10: Fitted Parameters for Output Forecasting Model by Manufacturing Industry

NAICS	Industry	Coefficients of Significant Dependent Variables in Fitted Model for Ln_Output as Dependent: Variable				Adjusted R Square for Fitted Model
		Intercept	Ln_Emp	Ln_Lab_Prod	Ln_Cap_Prod	
31-33	Manufacturing	4.17	0.81	0.83	.	0.81
311-312	Food and beverage and tobacco products	2.00	0.97	0.96	.	0.95
313-314	Textile mills and textile product mills	2.09	0.94	0.80	.	1.00
315-316	Apparel and leather and applied products	0.00	0.96	0.97	0.08	1.00
321	Wood products	1.27	1.00	0.95	.	0.98
322	Paper and paper products	4.95	0.74	0.61	.	0.97
323	Printing and related support activities	0.00	1.06	1.11	.	0.95
324	Petroleum and coal products	7.22	0.44	0.81	0.09	0.94
325	Chemicals	3.86	0.80	0.86	0.08	0.99

[58]U.S. Bureau of Labor Statistics (BLS), Productivity Data, National Labor Productivity and Costs, Total Factor Productivity, Information Processing Equipment Costs, and Intellectual Property Products Costs for Major Sectors and Major Industries, 1987-2023.

[59]U.S. Bureau of Labor Statistics (BLS), Employment and Output Projections, National Annual Average Employment and Output Projections by Industry, 2023-2033.

NAICS	Industry	Coefficients of Significant Dependent Variables in Fitted Model for Ln_Output as Dependent: Variable				Adjusted R Square for Fitted Model
		Intercept	Ln_Emp	Ln_Lab_Prod	Ln_Cap_Prod	
326	Plastics and rubber products	3.90	0.79	0.75	.	0.98
327	Nonmetallic mineral products	0.87	0.96	1.14	.	0.99
331	Primary metals	1.47	1.02	1.07	.	0.97
332	Fabricated metal products	2.98	0.87	0.80	.	0.88
333	Machinery	0.00	1.09	1.16	.	0.95
334	Computer and electronic products	0.00	1.11	1.05	.	0.95
335	Electrical equipment and appliances	1.95	0.99	0.90	.	0.99
336	Transportation equipment	0.00	1.13	1.14	.	0.95
337	Furniture and related products	1.43	0.95	0.92	.	0.99
339	Miscellaneous manufacturing	3.09	0.72	0.86	0.06	0.99

Table 3.1.6-11: U.S. BLS Output Projections based Growth Factors by Manufacturing Industry

NAICS	Industry	2023-2050 Output Growth Factor
311-312	Food and beverage and tobacco products	1.51
313-314	Textile mills and textile product mills	0.95
315-316	Apparel and leather and applied products	0.82
321	Wood products	1.32
322	Paper and paper products	1.05
323	Printing and related support activities	0.77
324	Petroleum and coal products	1.42
325	Chemicals	1.50
326	Plastics and rubber products	1.11
327	Nonmetallic mineral products	1.07
331	Primary metals	1.50
332	Fabricated metal products	1.19
333	Machinery	1.13
334	Computer and electronic products	1.80
335	Electrical equipment and appliances	1.32
336	Transportation equipment	1.46
337	Furniture and related products	1.08
339	Miscellaneous manufacturing	1.58

16. Under the 2050 **Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario** only, apply elasticity factors of change in productivity for unit change robot density, for top (more mature), middle and bottom (less mature) robot adopting industries[60] to estimate additional productivity increase by industry due to increase in industrial robot adoption (see Table 3.1.6-13). This will result in a slight upward adjustment to *Future Sales* $GF_{i,j}^{VA}$.

[60] U.S. Department of Commerce, International Trade Administration, 2020, Robots and the Economy - The Role of Automation in Driving Productivity Growth.

Table 3.1.6-12: Future Year (2050) Industrial Robot Adoption related Additional Productivity Growth Factor

NAICS Industry Code	NAICS Industry	Level of Industrial Robot Adoption	Elasticity in Change in Productivity in terms of Change in Robot Density	Additional Productivity Growth Factor due to Increase in Robot Adoption
11	Agriculture, Forestry, Fishing and Hunting	Bottom	0.0510	1.10
21	Mining, Quarrying, and Oil and Gas Extraction	Bottom	0.0510	1.10
22	Utilities	Middle	0.0084	1.02
23	Construction	Middle	0.0084	1.02
61	Educational Services	Middle	0.0084	1.02
311	Food manufacturing	Top	0.0049	1.01
312	Beverages and tobacco products	Top	0.0049	1.01
313	Textile mills	Bottom	0.0510	1.02
314	Textile product mills	Bottom	0.0510	1.02
315	Apparel	Bottom	0.0510	1.02
316	Leather and allied products	Bottom	0.0510	1.02
321	Wood products	Top	0.0049	1.01
322	Paper and paper products	Top	0.0049	1.01
323	Printing and related support activities	Top	0.0049	1.01
324	Petroleum and coal products	Top	0.0049	1.01
325	Chemicals	Top	0.0049	1.01
326	Plastics and rubber products	Top	0.0049	1.01
327	Nonmetallic mineral products	Top	0.0049	1.01
331	Primary metals	Top	0.0049	1.01
332	Fabricated metal products	Top	0.0049	1.01
333	Machinery	Top	0.0049	1.01
334	Computer and electronic products	Top	0.0049	1.01
335	Electrical equipment and appliances	Top	0.0049	1.01
336	Transportation equipment	Top	0.0049	1.01
337	Furniture and related products	Top	0.0049	1.01
339	Miscellaneous manufacturing	Top	0.0049	1.01

17. For NAICS sectors 11, 21, 22, 23, 31-33 and 48-49, apply the future year (2050) sales growth factors by Virginia geography estimated in Steps #14 and #15 to estimate future year (2050) sales by industry *i* and Virginia geography *j*.
    $Future\ Total\ Sales\ \%_{i,j}^{VA} = Future\ Total\ Sales\ GF_{i,j}^{VA} \times Base\ Total\ Sales\ \%_{i,j}^{VA}$

    Where:
    - $Future\ Total\ Sales\ GF_{i,j}^{VA}$: future year (2050) sales growth factors by industry *i* by Virginia geography *j*
    - $Base\ Total\ Sales\ \%_{i,j}^{VA}$: Base year (2023) sales growth factors by industry *i* and Virginia geography *j*

18. For NAICS sectors 11, 21, 22, 23, 31-33 and 48-49, add future year (2050) sales estimates from Steps #9, #14, #15, #16 and #17 to estimate future year (2050) sales for goods movement dependent sectors total.
    $Future\ GM\ Sales_j^{VA} = \sum_{i \in GM} Future\ Sales_{i,j}^{VA}$

    Where:
    - *GM*: Goods movement dependent NAICS sectors 11, 21, 22, 23, 31-33, 42, 44-45 and 48-49

Estimate Additive Manufacturing or 3D Printing Market Penetration for years 2023 and 2050

19. Estimate base year (2023) additive manufacturing or 3D printing market share of manufacturing sector total output.
$Base\ 3DP\ Sales\ Share^{VA} = Base\ 3DP\ Sales^{US} / Base\ Mfg\ Sales^{US}$

Where:

- $Base\ 3DP\ Sales^{US}$: Base year (2023) U.S. sales for additive manufacturing or 3D printing based on Precedence Research on U.S. 3D printing market size[61]
- $Base\ Mfg\ Sales^{US}$: Base year (2023) U.S. real gross output (sales) total for manufacturing sector in 2023 dollars based on U.S. BLS Productivity Data for U.S.[62]

20. Assume future year (2050) additive manufacturing or 3D printing market share of manufacturing sector total output, i.e., $Future\ 3DP\ Sales\ Share^{VA}$ at 7.5 percent as per a Congressional Research Service (CRS) report on 3D printing.[63] According to this report, 3D printing may account for 5-10 percent of manufacturing in the long-term (i.e., a mid-value of 7.5 percent).

Estimate Additive Manufacturing or 3D Printing Employment and Sales at the three-digit NAICS Industry for years 2023 and 2050

21. Apply additive manufacturing or 3D printing market penetration in Step #19 to base year (2023) manufacturing sector employment and sales by Virginia geography in Steps #1-8 and Step #10 and distribute among the three-digit NAICS industries that engage in additive manufacturing or 3D printing, to estimate base year (2023) additive manufacturing or 3D printing employment and sales by three-digit NAICS industry and Virginia geography.

$$Base\ 3DP\ Emp_{i,j}^{VA} = Base\ Mfg\ Emp_j^{VA} \times Base\ 3DP\ Sales\ Share^{VA} \times 3DP\ Industry\ Group\ K\ Sales\ Share_i^{US} \times \left(Base\ Mfg\ Emp_{i,j}^{VA} / \textstyle\sum_{i \in K} Base\ Mfg\ Emp_{i,j}^{VA}\right)$$

$$Base\ 3DP\ Sales_{i,j}^{VA} = Base\ Mfg\ Sales_j^{VA} \times Base\ 3DP\ Sales\ Share^{VA} \times 3DP\ Industry\ Group\ K\ Sales\ Share_i^{US} \times \left(Base\ Mfg\ Sales_{i,j}^{VA} / \textstyle\sum_{i \in K} Base\ Mfg\ Sales_{i,j}^{VA}\right)$$

Where:

- $Base\ Mfg\ Emp_j^{VA}$: Base year (2023) manufacturing sector employment for Virginia geography j
- $Base\ Mfg\ Sales_j^{VA}$: Base year (2023) manufacturing sector sales for Virginia geography j
- $3DP\ Industry\ Group\ K\ Sales\ Share_i^{US}$: Additive manufacturing or 3D printing industry group K's share of total additive manufacturing or 3D printing output
- $Base\ Mfg\ Emp_{i,j}^{VA}$: Base year (2023) employment for manufacturing for industry i and Virginia geography j
- $Base\ Mfg\ Sales_{i,j}^{VA}$: Base year (2023) sales for manufacturing industry i and Virginia geography j
- K: Group number for manufacturing industries that engage in additive manufacturing or 3D printing, shares of total additive manufacturing or 3D printing output are assumed for each group based on latest available research[64,65]
  - Group 1 consists of: 327 - Nonmetallic Mineral Product Manufacturing, 332 - Fabricated Metal Product Manufacturing, 333 - Machinery Manufacturing, 334 - Computer and Electronic Product Manufacturing and 335 - Electrical Equipment, Appliance, and Component Manufacturing, share assumed as 62.3 percent
  - Group 2 consists of: 315 - Apparel Manufacturing, 326 - Plastics and Rubber Products Manufacturing and 339 - Miscellaneous Manufacturing, share assumed as 16.2 percent
  - Group 3 consists of: 336 - Transportation Equipment Manufacturing, share assumed as 21.6 percent

[61]Precedence Research, 3D Printers Market Size, Share, and Trends 2025 to 2034, Available at: (last accessed on April 24, 2025)

[62]U.S. Bureau of Labor Statistics (BLS), Productivity Data, National Labor Productivity and Costs, Total Factor Productivity, Information Processing Equipment Costs, and Intellectual Property Products Costs for Major Sectors and Major Industries, 1987-2023.

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

[64]Machine Design Article, The State of Online 3D Printing, by Alkaios Bournias Varotsis dated May 24, 2019 (last accessed on April 24, 2025)

[65]Omar Jumaah, Doctoral Thesis, A Study on 3D Printing and its Effects on the Future of Transportation, The Center for Advanced Infrastructure and Transportation (CAIT), September 2018.

22. Repeat Step #21 using future year (2050) estimates of additive manufacturing or 3D printing market penetration in Step #20, future year (2050) manufacturing sector employment and sales by Virginia geography in Steps #1-8 and Step #15 and distribute among the three-digit NAICS industries that engage in additive manufacturing or 3D printing, to estimate future year (2050) additive manufacturing or 3D printing employment and sales by three-digit NAICS industry and Virginia geography.

$$Future\ 3DP\ Emp_{i,j}^{VA}$$
$$= Future\ Mfg\ Emp_{j}^{VA} \times Future\ 3DP\ Sales\ Share^{VA} \times 3DP\ Industry\ Group\ K\ Sales\ Share_{i}^{US}$$
$$\times \left(Future\ Mfg\ Emp_{i,j}^{VA} \,/\, \textstyle\sum_{i\in K} Future\ Mfg\ Emp_{i,j}^{VA}\right)$$

$$Future\ 3DP\ Sales_{i,j}^{VA}$$
$$= Future\ Mfg\ Sales_{j}^{VA} \times Future\ 3DP\ Sales\ Share^{VA} \times 3DP\ Industry\ Group\ K\ Sales\ Share_{i}^{US}$$
$$\times \left(Future\ Mfg\ Sales_{i,j}^{VA} \,/\, \textstyle\sum_{i\in K} Future\ Mfg\ Sales_{i,j}^{VA}\right)$$

Estimate Additive Manufacturing or 3D Printing share of total goods movement dependent sectors output for years 2023 and 2050

23. Estimate base year (2023) additive manufacturing or 3D printing market share of goods movement dependent sectors total output by dividing base year (2023) additive manufacturing or 3D printing sales in Step #21 by base year (2023) goods movement dependent sectors total sales in Step #13.
$$Base\ 3DP\ Share_{i}^{VA} = Base\ 3DP\ Sales_{i}^{VA} / Base\ GM\ Sales_{i}^{VA}$$

24. Repeat Step#23 to estimate future year (2050) additive manufacturing or 3D printing market share of goods movement dependent sectors total output by dividing future year (2050) additive manufacturing or 3D printing sales in Step #22 by future year (2050) goods movement dependent sectors total sales in Step #18.
$$Future\ 3DP\ Share_{i}^{VA} = Future\ 3DP\ Sales_{i}^{VA} / Future\ GM\ Sales_{i}^{VA}$$

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):

- US Bureau of Labor Statistics Employment Data for Virginia, 2023[1]
- Woods & Poole's Employment Estimates for Virginia, 2023 and 2050[2]
- U.S. Bureau of Labor Statistics (BLS) STEM Occupations Share of All Occupations by 2-Digit NAICS Industry[3], Ten-year Occupation Projections[4]
- Data sources used Macrotrend #6 to develop employment growth scenarios

[1] U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data, Annual Average Employment by Industry, 2023

[2] Woods and Poole via CDM Smith License, Complete Economic and Demographic Data Source (CEDDS) accessed via CDM Smith's Intranet, Inc. Virginia Statewide and County Projections to 1969-2060

[3] US Bureau of Labor Statistics (BLS), Occupational Employment and Wage Statistics (OEWS), Science, technology, engineering, and mathematics (STEM) data sets, May 2023, Downloaded on July 3, 2025.

[4] US Bureau of Labor Statistics (BLS), National Occupational Projections, 2023-2033

Calculations

For estimated changes in population and industry employment by location:

1. Gather base year (2023) employment data from U.S. BLS.
2. Apply employment forecasts, 2023-2050, from Woods & Poole and other methodologies used to develop employment growth scenarios. Report employment estimates for NAICS 54 - professional services sector under the base year (2023) and future year (2050) employment growth scenarios. Under the Low
3. Gather industry-specific occupational mix by Virginia geography for the datasets of base year (2023) and future year (2050) employment growth scenarios. Identify shares of STEM occupations for each dataset and summarize associated STEM employment estimates. Based on Tables 3.1.7-1 and 3.1.7-2, a few key observations are as follows:
   a. Future year (2050) STEM occupations and professional services sector employment follow the total employment pattern for the high and medium employment growth scenarios. However, for the low employment growth scenario due to increase in AI-skilled job share (which are primarily STEM type), STEM occupations employment increases above the medium employment growth scenario, while professional services sector employment remains at the same level as the medium scenario.
   b. At statewide level STEM occupations employment ranges from 371 thousand persons under the medium scenario to 445 thousand persons under the high scenario. This is 29-55 percent higher than the base year (2023) STEM occupations employment.
   c. Similarly, at statewide level professional services sector employment ranges from 677 thousand persons under the low and medium scenarios to 811 thousand persons under the high scenario. This is 43-71 percent higher than the base year (2023) professional services sector employment. The growth range in total employment for comparison is just 15-39 percent, which implies that in the future year (2050) professional services sector is expected to grow in share of total employment.

Table 3.1.7-1: Statewide Employment Growth by Scenario (Percent Change)

Metric	Base Year (2023)	Low Scenario	Medium Scenario	High Scenario
STEM Occ. Emp. (2050)	287,904	+29%	+42%	+55%
Prof. Services Sector Emp. (2050)	474,713	+43%	+43%	+71%

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: The drivers of this macrotrend include:

- Advancement of workplace communication technology and collaboration tools[1]
- Availability, reliability, and speed of broadband services[2]
- Growth in high-end knowledge work tasks and product innovation with assistance from AI[3]

Data Sources:

- U.S. Bureau of Labor Statistics Employment Data for Virginia, 2023[4]
- Woods & Poole's Employment Estimates for Virginia, 2023 and 2050[5]
- U.S. Census, American Community Survey (ACS), Historical Work from Home Shares by Occupation Category[6]
- Data sources used *Macrotrend #6* to develop employment growth scenarios

[1] Frost & Sullivan, 2024. State of the Global Video Conferencing Devices Market, Report for Logitech.

[2] Pew Research Center, 2024, Internet, Broadband Fact Sheet

[3] Dell'Acqua, F. and McFowland III, E. and Mollick, E. R. and Lifshitz-Assaf, H. and Kellogg, K. and Rajendran, S. and Krayer, L. and Candelon, F. and Lakhani, K. R., 2023, Navigating the Jagged Technological Frontier: Field Experimental Evidence of the Effects of AI on Knowledge Worker Productivity and Quality. Harvard Business School Technology & Operations Mgt. Unit Working Paper No. 24-013, The Wharton School Research Paper.

[4] U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data, Annual Average Employment by Industry, 2023

[5] Woods and Poole via CDM Smith License, Complete Economic and Demographic Data Source (CEDDS) accessed via CDM Smith's Intranet, Inc. Virginia Statewide and County Projections to 1969-2060

[6] U.S. Census, 2019-2023 American Community Survey (ACS) 5-Year Estimates, Means of Transportation to Work by Occupation.

Calculations:

For estimated changes in work from home share employment by location:

1. Gather base year (2023) employment data from U.S. BLS.
2. Apply employment forecasts, 2023-2050, from Woods & Poole and other methodologies for employment growth scenarios.
3. Gather industry-specific occupational mix by Virginia geography for the datasets of base year (2023) and future year (2050) employment growth scenarios. Aggregate the individual SOC occupation shares to SOC occupation category shares for each dataset. Occupational categories include: Management, business, science, and arts occupations (SOC 11-0000 to 29-0000), Service occupations (SOC 31-0000 to 39-0000), Sales and office occupations (SOC 41-0000 to 43-0000), Natural resources, construction, and maintenance occupations (SOC 45-0000 to 49-0000), Production, transportation, and material moving occupations (SOC 51-0000 to 53-0000).
4. Apply work from home shares by occupation category to occupation category share of total employment to estimate overall work from home share in each Virginia geography under the base year (2023) and future year (2050) employment growth scenarios. Multiply the overall work from home share with total employment in Virginia geography to compute work from home employment. Based on Table 3.1.8-1, a few key observations are as follows:
   a. Future year (2050) work from home employment follows the total employment growth scenarios and at statewide level work from home employment ranges from 661 thousand persons under the low scenario to 793 thousand persons under the high scenario. This is 20-44 percent higher than the base year (2023) work from home employment.
   b. Work from home share of total employment does not show a noticeable change even under the low scenario with an increase in AI-skilled jobs share that are work from home friendly.

Table 3.1.8-1: Statewide Work from Home Employment Forecast (2050)

Metric	Base Year WFH Emp. (2023)	Low Scenario	Medium Scenario	High Scenario
Projected Work from Home Emp.	552,851	661,451	663,212	793,469
Share of Total Emp.	15%	15%	15%	15%
Change (2023-2050)	-	+20%	+20%	+44%

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:
- U.S. Census Historical Population Data for Virginia, 2023[1]
- Woods & Poole's Population Estimates for Virginia, 2023 and 2050[2]
- Data sources used Macrotrend #6 to develop employment growth scenarios

[1] U.S. Census, Vintage 2023 Annual Resident Population Estimates by Selected Age Groups and Sex: April 1, 2020 to July 1, 2023

[2] Woods and Poole via CDM Smith License, Complete Economic and Demographic Data Source (CEDDS) accessed via CDM Smith's Intranet, Inc. Virginia Statewide and County Projections to 1969-2060

Calculations:

For estimated changes in age 65+ population by location:

1. Gather base year (2023) population and Age 65+ population from U.S. Census.
2. Apply population and Age 65+ forecasts, 2023-2050, from Woods & Poole and other methodologies used to develop employment growth scenarios. Adjust population only under the 2050 Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario, proportional to the geographical shifts in employment estimated due to increase in Gen AI development and use. Adjust Age 65+ also proportionately. Based on Table 3.1.9-1 on the next page, a few key observations are as follows:
   a. Future year (2050) population is expected to be the same at the statewide level under all employment growth scenarios. However, at VA geography level, population would have small geographical shifts from Northern Virginia, Richmond and Salem/New River Valley/Blacksburg regions to Hampton Roads region under the low employment growth scenario due to job displacement effects of AI.
   b. Although, change in Age 65+ population for VA geographies of Northern Virginia, Richmond, Salem/New River Valley/Blacksburg and Hampton Roads changes under the low employment growth scenario, age 65+ share of total population is assumed the same under all future year (2050) scenarios.

Table 3.1.9-1: Statewide Population Forecast for Age 65+ Cohort (2050)

Metric	Base Year Age 65+ pop. (2023)	Low Scenario	Medium Scenario	High Scenario
Projected Age 65+ pop.	552,851	2,226,563	2,226,563	793,469
Share of Total Pop.	17%	21%	21%	21%
Change (2023-2050)	-	+49%	+49%	+49%

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: The drivers of this macrotrend include:
- 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:
- U.S. Census Historical Population Data for Virginia, 2023[1]
- US Bureau of Labor Statistics Employment Data for Virginia, 2023[2]
- Woods & Poole's Population, Employment and Household income Estimates for Virginia, 2023 and 2050[3]
- Data sources used *Macrotrend #6* to develop employment growth scenarios

Calculations:
For estimated changes in population and industry employment by location:
1. Gather base year (2023) population from U.S. Census and employment data from U.S. BLS.
2. Gather base year (2023) mean household income from Woods & Poole data.
3. Apply population, employment and mean household income forecasts, 2023-2050, from Woods & Poole and other methodologies used to develop employment growth scenarios. Adjust population only under the 2050 Low (W&P Emp. Adj. to Wrk. Age Pop. + AI/Auto.) Scenario, proportional to the geographical shifts in employment estimated due to increase in Gen AI development and use. Based on Tables 3.1.10-1hrough 3.1.10-1-3 on the following pages, a few key observations are as follows:

[1] U.S. Census, Vintage 2023 Annual Resident Population Estimates by Selected Age Groups and Sex: April 1, 2020 to July 1, 2023

[2] U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data, Annual Average Employment by Industry, 2023

[3] Woods and Poole via CDM Smith License, Complete Economic and Demographic Data Source (CEDDS) accessed via CDM Smith's Intranet, Inc. Virginia Statewide and County Projections to 1969-2060

a. Future year (2050) employment follows the high, medium and low scenario definitions and at statewide level this ranges from 4.34 million persons under the low scenario to 5.24 million persons under the high scenario. This is 15-39 percent higher than the base year (2023) employment.
b. Future year (2050) population is expected to be the same at the statewide level under all employment growth scenarios. However, at VA geography level, population would have small geographical shifts from Northern Virginia, Richmond and Salem/New River Valley/Blacksburg regions to Hampton Roads region under the low employment growth scenario due to job displacement effects of AI.
c. Effects of the employment growth scenarios on household income are not evaluated. Hence, a single forecast for mean household income based on Woods & Poole is reported.

Table 3.1.10-1: Statewide Employment Forecast (2050)

Metric	Base Year Age 65+ pop. (2023)	Low Scenario	Medium Scenario	High Scenario
Projected Age 65+ pop.	3,783,695	4,335,507	4,374,538	5,244,437
Change (2023-2050)	-	+15%	+16%	+39%

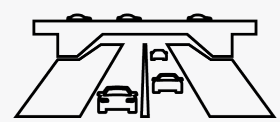
Table 3.1.10-2: Statewide Population and Mean Household Income Forecast (2050)

Metric	Base Year pop. (2023)	Forecast year (2050)	Change (2023-2050)
Total Population	8,715,698	10,599,119	+ 21.61%
Mean Household Income	$154,978	$232,127	+ 50%

3.2. Step 2: Develop Metrics for CTB Goals

Step 2 identifies metrics for the CTB's five Goals and associated Objectives[1] (Table 3.2-1). These metrics were established after an evaluation of availability of research, tools, and methods, and are considered fundamental blocks upon which a more comprehensive set of metrics can be developed in the future. Goal Metrics stand in for one or more aspects of the relevant goal and allow for progress toward the goal to be quantitatively tracked.

Table 3.2-1: Metrics for CTB Goals

Goals	Objectives	Metrics for CTB Goals and Objectives
Goal A: Transportation System Safety Reduce fatalities and serious injuries to make the transportation network safer for the traveling public	A.1. Reduce the number and rate of motorized fatalities and serious injuries through implementation of the Strategic Highway Safety Plan.	Safety Index (Safety Index - Estimated Change in Number of Crashes with Fatalities + Serious Injuries Due to VTrans Macrotrends) 
	A.2. Reduce the number of non-motorized fatalities and serious injuries through implementation of the Strategic Highway Safety Plan.	
	A.3. Reduce fatalities and serious injuries by implementing annual Safety Performance Targets in Public Transportation Agency Safety Plans.	
Goal B: System Preservation Provide well-maintained and managed transportation infrastructure and services across the Commonwealth.	B.1. Obtain the following outcomes through the implementation of the recommendations from VDOT's Maintenance and Operations Comprehensive Review. ▪ Meet long-term sustainable pavement and bridge performance targets adopted by the Board. ▪ Maintain VDOT's special structures in accordance with the annually updated 50-year special structures plan. ▪ Meet routine maintenance best practices performance metrics.	Roadways at Risk from Flooding 
	B.2. Ensure transit state of good repair through the prioritization of investments and implementation of performance targets in Transit Asset Management plans.	
	B.3. Ensure transit state of good repair through the prioritization of state capital investments in public transportation.	
	B.4. Maximize the benefits of the Rail Preservation Fund through effective allocations to Class 2 (Shortline/Freight) and Class 3 (Passenger Rail) track improvements.	
Goal C: Economic Competitiveness through Travel Time Reliability Encourage economic competitiveness and prosperity by improving travel time reliability by minimizing congestion and considering modal options.	C.1. Improve travel time reliability and throughput by reducing the amount of travel that takes place in congested conditions by prioritizing performance-based investments, including operational improvements.	Vehicles Miles Traveled (VMT) Index (Estimated Change due to VTrans Macrotrends) 
	C.2. Improve freight throughput through the implementation of the Virginia Freight Plan and 2022 Statewide Rail Plan.	
	C.3. Improve transit efficiency and effectiveness by implementing system-wide and route-level performance standards established in Transit Strategic Plans and Transit Development Plans.	

[1] Commonwealth Transportation Board, Action on Modifying the VTrans Vision, Guiding Principles, Goals, and Objectives and Action on Performance Measures and Targets, April, 15, 2025.

Goals	Objectives	Metrics for CTB Goals and Objectives
Goal D: Inter-Connected Systems and Services Provide an integrated multimodal transportation system for better accessibility and travel options.	D.1. Create multimodal redundancy to support network resiliency by providing alternative modes of travel where appropriate.	Shared Mobility Index (Switchable Urban Auto SOV VMT to Micromobility and TNC/Ridesourcing) 
	D.2. Increase bus ridership by improving bus stop condition and accessibility.	
	D.3. Enhance freight rail movements to support economic development and freight fluidity for the Port of Virginia by implementing the 2022 Statewide Rail Plan.	
	D.4. Support economic development initiatives through investments in site accessibility.	
Goal E: Environmental Stewardship Provide transportation solutions that enhance the quality of life while preserving agricultural, natural, historical, and cultural resources.	E.1. Deliver transportation solutions that consider watershed impacts, habitat preservation, and required environmental regulatory review.	Tailpipe Emissions Index (Estimated Change Due to VTrans Macrotrends) 
	E.2. Implement solutions to support the attainment of National Ambient Air Quality Standards.	

3.3. Step 3: Estimate Impact of Macrotrends on Goal Metrics

Step 3 evaluates the cumulative impact of one or more of ten Macrotrends on each of the Goal Metrics (Table 3.3-1) and calculates a range of possible impacts on Virginia's transportation system performance for 2050. 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 may influence those that are later in the order of influence, but not typically the reverse.

Table 3.3-1: Order of Influence of Macrotrends and Influence of Macrotrends on Goal Metrics

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	Included in the 2050 Business-as-usual Scenario				
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 Services Industry Macrotrend # 10: Population and Employment Shift	Included in the 2050 Business-as-usual Scenario				
	Cumulative Impacts	•	•	•	•	•

• Quantified in Step 3

3.3.1. Impact of Step 1 Macrotrends on CTB Goal A Metrics

Description: As outlined in Section 3.2, estimated change in number of crashes involving fatalities and serious injuries is used as a metric to assess impact of VTrans Macrotrends on Goal A: Transportation System Safety.

Significance: A change in the number of crashes involving fatalities and serious injuries can impact CTB Goal A 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 (2050) 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 of automation (Vehicle Automation Levels 1–4) for the low, medium, and high 2050 scenarios for VTrans Macrotrend #2: Adoption of Highly Autonomous Vehicles.
2. Utilize Li & Kockelman to establish a crosswalk between vehicle automation safety applications (e.g., FCW, AEB, LKA) and collision types (e.g., rear-end, lane departure).
3. Establish baseline crashes by severity. Using 2024 Virginia crash statistics, compile baseline counts by severity group K (fatalities), A (serious injuries), B (visible), C (non-visible), and O (property-damage-only).
4. Derive severity-level reduction ratios from safety application effectiveness.
   a. From Li & Kockelman's effectiveness matrix (Conservative / Moderate / Aggressive), map application-specific effectiveness to 2024 crashes by collision type.
   b. Aggregate to severity-specific reduction ratios by comparing the implied prevented crashes to the 2024 baseline for each severity group.
   c. Produce two reduction ratio sets (severity-level):
      – $r(cons)_s$ for Conservative effectiveness (used for L1/L2).
      – $r(aggr)_s$ for Aggressive effectiveness (used for L4).

      Where, s ϵ {K, A, B, C, O}).
5. Assign reduction ratios by automation level.
   – Levels 1–2 (driver-assist): apply $r(cons)_s$
   – Level 4 (high automation): apply $r(aggr)_s$
6. Compute scenario-weighted reduction by severity. For each scenario q ϵ {low, med, high} with 2050 AV penetrations by level of automation:

   $$Crash\ Reduction\ s = (P_q^{L1\text{–}2} * r(cons)_s) + (P_q^{L3\text{–}4} * r(aggr)_s)$$

   Where:
   - $P_q^{L1\text{–}2}$ is the market penetration of Level 1-2 AVs
   - $P_q^{L3\text{–}4}$ is the market penetration of Level 3-4 AVs
   - q is the projected scenario of market penetration

Table 3.3.1-1: Potential Crash Rate Reductions by AV Market Penetration

	Low Estimate	Medium Estimate	High Estimate
Fatal Injury - K	34%	39%	50%
Severe Injury - A	43%	48%	59%
Moderate Injury - B	56%	61%	71%
Minor Injury - C	64%	69%	78%
Property Damage Only - O	67%	72%	80%

Estimate the impact of change in vehicle miles traveled (2050) derived from Section 3.3.1 on safety

7. Account for ΔVMT (2050). 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. For crash types other than K and A, crashes compared with baseline are considered the safety index.

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

   $\textit{Safety index}_s = \Delta VMT * (1 - \textit{potential crash reductions})$

   Where:
   - $\textit{Safety index}_s$ is the safety index for crash severity 's'
   - *ΔVMT* is the change in VMT calculated for the low, medium, and high scenarios in Section 3.3.1.
   - *Potential crash rate reduction* is the estimate for the change in crash rate shown in the calculation step # 6, Table 3.3.3-1.

Table 3.3.1-2: Crashes Compared to Baseline by Scenario

Crashes	Low Estimate	Medium Estimate	High Estimate
Fatal Injury - K	66%	62%	54%
Severe Injury - A	57%	53%	44%
Visible Injury - B	44%	40%	31%
Non-Visible Injury - C	36%	31%	24%
Property Damage Only - O	33%	28%	21%

8. For fatal and serious injury crashes, the combined safety index is calculated by creating a weighted safety index based on the proportional split in Virginia between K and A crashes using 7-year (2017-2024) average crash counts. For the statewide analysis, this translates to the following weights: 12.3 percent (K) and 87.7 percent (A).

   Δ Safety Index (2050)
   = 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 3.3.3-2
   - *A crashes* is the estimated serious injury crashes compared with baseline shown in Table 3.3.3-2
   - *K counts* is the 7-year (2017-2024) average fatal injury crash count in Virginia.[6]
   - *A counts* is the 7-year (2017-2024) average serious injury crash count in Virginia.[7]

Step 3: Impact of VTrans Macrotrends on CTB Goal A in the Year 2050

The results of calculation step # 8 for the statewide analysis are included in Table 3.3.3-3 and should be interpreted as follows:
- Low-impact Scenario: Number of crashes involving fatalities and serious injuries is estimated to decrease by 42 percent over the 2050 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 46 percent over the 2050 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 55 percent over the 2050 no-build scenario (absence of VTrans Macrotrends - Step 1)

[6] (Aggregated) Virginia Department of Transportation (2024). Virginia Roads, Accessed December 28, 2024

[7] (Aggregated) Virginia Department of Transportation (2024). Virginia Roads, Accessed December 28, 2024

Table 3.3.1-3: Estimated Impact of VTrans Macrotrends on CTB Goal A in Year 2050

CTB Goal	Metrics for CTB Goal	Low Estimate	Medium Estimate	High Estimate
Goal A: Reduce fatalities and serious injuries to make the transportation network safer for the traveling public.	Safety Index_{K+A} (Estimated Change in Number of Crashes with Fatalities + Serious Injuries Due to VTrans Macrotrends)	0.58	0.54	0.45
	Safety Index_{B} (Estimated Change in Number of Crashes with Visible Injuries Due to VTrans Macrotrends)	0.44	0.40	0.31
	Safety Index_{C} (Estimated Change in Number of Crashes with Non- Visible Injuries Due to VTrans Macrotrends)	0.36	0.31	0.24
	Safety Index_{O} (Estimated Change in Number of Property Damage Only Crashes Due to VTrans Macrotrends)	0.33	0.28	0.21

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 are not captured since the outputs are over the 2050 no-build scenario which assumes 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 cyclists.
- 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.

3.3.2. Impact of Step 1 Macrotrends on CTB Goal B Metrics

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:

Table 3.3.2-1: Data Sources by Scenario for Estimating Risk from Flooding Events

Hazard	Data Source of Estimated Hazard	Low Scenario	Medium Scenario	High Scenario
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

Source of Methodology: The methodology is based on Federal Highway Administration's FHWA Vulnerability Assessment Scoring Tool (VAST) for each of the three scenarios. 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.

- **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.

Calculations: 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.

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 28 and 29 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 28 and 29 to calculate a vulnerability score for each asset by hazard type.

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

Table 3.3.2-2: Estimated Impact of VTrans Macrotrends on CTB Goal B in Year 2045[2]

CTB Goal	Metric 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

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

Table 3.3.2-3: 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[3]	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[3]	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%				

Table 3.3.2-4: 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[3]	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[3]	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[3]	100%				

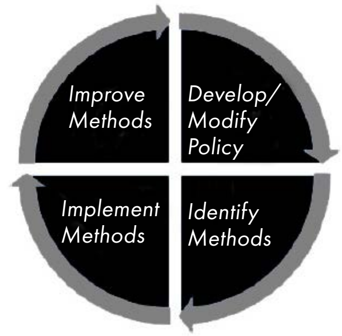
[3] Scores for Sensitivity, Adaptive Capacity, and Vulnerability are only developed if Exposure component indicates risk of inundation.

Table 3.3.2-5: Miles at Risk of Flooding by VDOT District and Planning District Commission

	Inland-Riverine Flooding (Roadway Segment Miles affected)			Storm Surge (Roadway Segment Miles affected)			Sea Level Rise (Roadway Segment Miles affected)		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
STATEWIDE									
Total	17,474	17,829	18,250	7,706	13,094	17,091	935	1,100	1,423
VDOT CONSTRUCTION DISTRICTS									
Bristol	2,966	3,049	3,165	-	-	-	-	-	-
Culpeper	1,314	1,320	1,344	-	-	-	-	-	-
Fredericksburg	1,260	1,291	1,332	2,056	2,790	3,326	270	329	471
Hampton Roads	1,270	1,343	1,376	5,386	9,763	12,945	617	723	887
Lynchburg	3,377	3,400	3,477	-	-	-	-	-	-
Northern Virginia	616	635	656	82	144	260	12	12	14
Richmond	2,415	2,442	2,473	177	393	552	37	37	52
Salem	2,771	2,837	2,896	-	-	-	-	-	-
Staunton	1,485	1,511	1,532	-	-	-	-	-	-
PLANNING DISTRICT COMMISSIONS									
Accomack-Northampton	151	181	183	1,276	1,540	1,771	197	266	368
Central Shenandoah	597	615	618	-	-	-	-	-	-
Central Virginia	1,237	1,258	1,285	-	-	-	-	-	-
Commonwealth Regional Council	1,304	1,306	1,331	-	-	-	-	-	-
Crater	901	906	920	96	167	213	18	18	19
Cumberland Plateau	795	820	840	-	-	-	-	-	-
George Washington	606	609	630	47	85	149	4	6	12
Hampton Roads	641	682	700	4,050	8,141	11,082	407	444	505
Lenowisco	801	842	895	-	-	-	-	-	-
Middle Peninsula	408	426	440	1,338	1,601	1,780	191	238	330
Mount Rogers	1,549	1,565	1,611	-	-	-	-	-	-
New River Valley	783	813	831	-	-	-	-	-	-
Northern Neck	246	257	262	671	1,104	1,397	75	84	129
Northern Shenandoah	799	806	816	-	-	-	-	-	-
Northern Virginia	616	635	656	82	144	260	12	12	14
Rappahannock-Rapidan	839	839	850	-	-	-	-	-	-
Richmond Regional	921	944	958	142	306	431	32	32	45
Roanoke Valley-Alleghany	599	615	629	-	-	-	-	-	-
Southside	1,010	1,012	1,026	-	-	-	-	-	-
Thomas Jefferson	861	868	891	-	-	-	-	-	-
West Piedmont	1,811	1,831	1,878	-	-	-	-	-	-

Limitations and Opportunities for Continuous Improvement

Figure 3.3.2-1: 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.
  - 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 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.

3.3.3. Impact of Step 1 Macrotrends on CTB Goal C Metrics

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 metrics for CTB priorities, such as safety and tailpipe emissions. Estimates of future VMT changes are presented at the statewide and county level.

Data Sources:

- Fare elasticity: Taiebat et al. and Cohen et al.[1]
- Effect of AVs on Operating Cost and VMT: Compostella[2]
- Vehicle Cost Elasticities: Dong et al.[3] (2012)
- VDOT's Daily Vehicle Miles Traveled Data for Virginia[4]
- Commute modes: FHWA[5]
- Vehicle Travel Information System (VTRIS) Average Truck Gross Weight and Payload Data for Virginia[6]
- Vehicle Inventory Use Survey (VIUS), National Short- and Long-Haul Shares by Truck Weight Class[7]

[1] 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

[2] 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.

[3] Jing Dong, Diane Davidson, Frank Southworth and Tim Reuscher, "Analysis of Automobile Travel Demand Elasticities With Respect To Travel Cost"

[4] VDOT, 2022, Vehicle miles traveled (VMT) by Physical Jurisdiction and by Federal Vehicle Class across All Roads.

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

[6] Vehicle Travel Information System (VTRIS), 2010-2014 (5-Year), W-3 Tables for Virginia, Average Gross Weight and Payload (lbs) for Trucks.

[7] U.S. Department of Commerce, Bureau of the Census, 2002 Vehicle Inventory and Use Survey (VIUS), Short-Haul (less than equal to 100 miles) and Long-Haul (more than 100 miles) Shares by Weight Class of Truck.

- Freight Analysis Framework (FAF) Value per Ton by Commodity Group and Long-Haul, Regional and Drayage Sourcing Shares for Virginia[8]
- National retail federation's rate of return assumptions of auto-based in-store purchases and online purchases of retail trade[9]
- World Bank's home delivery routes of e-commerce shipments stops per day[10]
- National Household Travel Survey's (NHTS) average trip length for shopping trip purposes by MSA size and availability of heavy rail[11]
- Average annual travel miles for Class 6 urban delivery truck[12]
- E-commerce mode split assumptions by MSA size[13]
- Percent of e-commerce deliveries asking for same-day delivery[14] and small (less than 55 pounds) unmanned aerial vehicle (UAV) or drone use share assumption for the same-day delivery[15]
- Small UAV or drone haul distance assumption[16]

Calculations:

Calculations to measure change in VMT in future year (2050) rely on outputs related to the following Macrotrends included in Section 3.1, Step 1. 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

The combined impact of Macrotrend # 2: Adoption of Highly Autonomous Vehicles (AV), Macrotrend # 3: Adoption of Electric Vehicles, Macrotrend # 4: Growth in Shared Mobility (Ridesharing 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[17] (adjusted to inflation).
2. Given that total vehicle cost in calculation step # 1 has different impacts on personal usage vehicles and on ride source vehicles, calculate two elasticities.

   a. Determine a change in travel demand elasticity of using an average of elasticities noted in various studies.[18]

[8] U.S. Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA), 2023, Freight Analysis Framework Version 5.6 (FAF v5.6), Tonnage and Value Summary for Commodities.

[9] National Retail Federation, 2024, Consumer Returns in the Retail Industry.

[10] The World Bank, 2019, Facilitating Trade and Logistics for E-Commerce: Building Blocks, Challenges and Ways Forward.

[11] Oak Ridge National Laboratory (ORNL), 2022, National Household Travel Survey (NHTS), Average trip length for shopping trip purposes by MSA size.

[12] ICF, 2019, Comparison of Medium- and Heavy-Duty Technologies in California, Final Report Prepared for California Electric Transportation Coalition and Natural Resources Defense Council.

[13] Under e-commerce, this Tech Guide assumes a split between pick-up at store plus drone, delivery van and delivery truck modes to be split as 10:20:70 for large MSA (over 1 million people), 5:10:85 for small MSA (less than 1 million people), and 0:5:95 for non-MSA. Drone delivery was considered to be an alternative to pick-up at store consumers.

[14] McKinsey & Company, 2016, Parcel delivery: The future of last mile.

[15] As per McKinsey, about 25 percent of consumers are asking for same-day deliveries. Of these, this Tech Guide assumes 50 percent to have the potential to be delivered by drones.

[16] 30-minute delivery window at 50 miles per hour drone speed and 6 minutes of changeover time

[17] 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.

[18] 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.

b. Determine a change in fare elasticity of using elasticities reported in Taiebat et al.[19] and Cohen et al.[20]

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

4. $b_{VMT} = p_{VC} * e$

Where:

- v is a vehicle type v out of all vehicle types V.
- b_{VMT} is the estimated VMT increase by vehicle type v.
- p_{VC} 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 3.1.4, calculation step # 9. Convert to percentage of all VMT for each scenario by dividing by 2050 Virginia VMT calculated in section 3.1.4 from Replica 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. Use standard deviation to determine the composition of internal combustion engine (ICE) vehicles, plug-in hybrid electric vehicles (PHEV), and electric vehicles (EV) in Virginia fleet shares for low/medium/high scenarios using fleet mix outputs from the three policy scenarios. These fleet shares are normalized to ensure the sum of all is 100 percent.

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

   $c_v = b \times a_v$

   $MT\_2\_3\_4\ (d) = \text{AV Market Penetration} * \sum_v V\, c_v$

   Where:

   - v is a vehicle type out of all vehicle types V.
   - a_v is the estimated share of fleet for vehicle type v.[21]
   - 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 Section 3.1.4, calculation step # 9.

   MT_4 = new 2050 micromobility mileage / 2050 private-auto VMT

   Where:

   - New 2050 micromobility mileage is the auto VMT that is expected to switch to micromobility by 2050. For the medium scenario, this is the micromobility switchable VMT for 2050 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.

[19] 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

[20] 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.

[21] 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.

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

Estimate daily automobile VMT avoided in future year (2050) due to e-commerce growth for each employment growth scenario.

9. For a given employment growth scenario, determine the future year (2050) annual increase in B2C e-commerce sales over the base year (2023).

   $Future\ E\text{-}com\ Sales\ Chg_j^{VA}$
   $= Future\ Output_{j,GM}^{VA} \times Future\ B2C\ Output\ Share_j^{VA} \times Future\ B2C\ E\text{-}com\ Sales\ \%_j^{VA}$
   $- Base\ Output_{j,GM}^{VA} \times Base\ B2C\ Output\ Share_j^{VA} \times Base\ B2C\ E\text{-}com\ Sales\ \%_j^{VA}$

   Where:
   - *Future Output*$_{j,GM}^{VA}$: Future year (2050) goods movement dependent sectors total output in Virginia geography *j* based on Step 1 Calculations for Macrotrend #5 and under a given employment growth scenario
   - *Future B2C Output Share*$_j^{VA}$: Future year (2050) retail trade or B2C total sales share of out of goods movement dependent sectors total output in Virginia geography *j* based on Macrotrend #5 and under a given employment growth scenario
   - *Future B2C E-com Sales %*$_j^{VA}$: Future year (2050) retail trade or B2C e-commerce sales share of out of total B2C sales in Virginia geography *j* based on Macrotrend #5 and under a given employment growth scenario
   - *Base Output*$_{j,GM}^{VA}$: Base year (2023) goods movement dependent sectors total output in Virginia geography *j* based on Macrotrend #5
   - *Base B2C Output Share*$_j^{VA}$: Base year (2023) retail trade or B2C total sales share of out of goods movement dependent sectors total output in Virginia geography *j* based on Macrotrend #5
   - *Base B2C E-com Sales %*$_j^{VA}$: Base year (2023) retail trade or B2C e-commerce sales share of out of total B2C sales in Virginia geography *j* based on Step 1 Calculations for Macrotrend #5
   - *j*: index for Virginia geographies that include statewide and metropolitan statistical areas (MSAs) of Blacksburg-Christiansburg-Radford, Charlottesville, Harrisonburg, Lynchburg, Richmond, Roanoke, Staunton-Stuarts Draft, and Virginia parts of Kingsport-Bristol, Virginia Beach-Chesapeake-Norfolk, Washington-Arlington-Alexandria and Winchester.

10. Convert the increase in annual B2C e-commerce sales in Step #1 to annual tons of e-commerce using average value per ton for a B2C e-commerce commodity. Use US BTS and FHWA's Freight Analysis Framework Version 5.6 (FAF v5.6) database,[22] based on which the value per ton for "mixed freight" goods traveling within Virginia was estimated as $5,672 per ton, which was assumed to be a typical value per ton for retail trade or B2C e-commerce commodities.

    $Future\ E\text{-}com\ Tons\ Chg_j^{VA} = Future\ E\text{-}com\ Sales\ Chg_j^{VA} \times ValPerTon_{E\text{-}com}^{FAF}$

    Where:
    - *ValPerTon*$_{E\text{-}com}^{FAF}$: FAF v5.6 based value per ton for B2C e-commerce commodity

11. Estimate future year (2050) non-commercial daily auto VMT avoided over base year (2023) at the Virginia MSA level by taking a difference between shop at store auto VMT avoided before the e-commerce change and pick up at store auto VMT added after the e-commerce change. Daily Auto VMT avoided before the e-commerce change is calculated for 100 percent of the annual change in e-commerce tonnage, while daily auto VMT added after the e-commerce change is calculated for the mode share of pick up at store by MSA and after removing the small UAV or drone delivery share. An annual to daily conversion factor of 300 was used instead of 365 (typical number of days in a year) to represent peak daily demand for e-commerce goods.

    a. Daily auto VMT avoided before the e-commerce change is calculated as follows:
       $Future\ Dly\ Auto\ VMT\ Chg_j^{VA,Pre} = Future\ E\text{-}com\ Tons\ Chg_j^{VA} \times (1+ Return\%^{Shop\ at\ Store}) \times AvgTripLen^{Auto} / Payload^{Auto} \times 300)$

    b. Daily auto VMT added after the e-commerce change is calculated as follows:
       $Future\ Dly\ Auto\ VMT\ Chg_j^{VA,Post}$
       $= (Future\ E\text{-}com\ Tons\ Chg_j^{VA} - Drone\ E\text{-}com\ Tons\ Chg_j^{VA}) \times (1+ Return\%^{Online}) \times AvgTripLen^{Auto} \times E\text{-}com\ Mode\%^{Auto} / Payload^{Auto} \times 300$

[22] U.S. Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA), 2023, Freight Analysis Framework Version 5.6 (FAF v5.6), Tonnage and Value Summary for Commodities.

$Future\ Drone\ E\text{-}com\ Tons\ Chg_i^{VA}$
$= Future\ Output_{i,GM}^{VA} \times Future\ B2C\ Output\ Share_i^{VA} \times Future\ B2C\ E\text{-}com\ Sales\ \%_i^{VA}$
$\times Future\ Drone\ Delivery\%_{E\text{-}com}^{US}$
$- Base\ Output_{GM}^{VA} \times Base\ B2C\ Output\ Share_i^{VA} \times Base\ B2C\ E\text{-}com\ Sales\ \%_i^{VA}$
$\times Base\ Drone\ Delivery\%_{E\text{-}com}^{US}$

Where:

- $Return\%^{Shop\ at\ Store}$: Rate of return for shop at store, which is 16.7 percent[23]
- $Return\%^{Online}$: Rate of return for shop at store, which is 20.2 percent[24]
- $AvgTripLen^{Auto}$: Average two-way trip length for shopping trip purpose by auto, with the lowest value of 9.4 miles for Washington-Arlington-Alexandria MSA, 11.4 miles for Kingsport-Bristol, Lynchburg, Richmond, Roanoke and Virginia Beach-Norfolk-Newport News MSAs, and 17.4 miles for all other MSAs and Non-MSA, determined using NHTS averages based on MSA population range and availability of heavy rail[25]
- $Payload^{Auto}$: Assumed as 2,500 pounds per auto[26]
- $E\text{-}com\ Mode\%^{Auto}$: mode share of auto for store pick or drone delivery assumed as 10 percent for large MSA (over 1 million people), 5 percent for small MSA (less than 1 million people), and 0 percent for non-MSA
- $Base\ Drone\ Delivery\%_{E\text{-}com}^{US}$: Assumed as zero percent
- $Future\ Drone\ Delivery\%_{E\text{-}com}^{US}$: Assumed to reach 50 percent of the 25 percent[27] for share of same-day e-commerce deliveries out of total e-commerce deliveries, i.e., 12.5 percent

c. Net daily auto VMT avoided due to the e-commerce change is calculated as follows:
$Future\ Dly\ Net\ Auto\ VMT\ Chg_i^{VA} = Future\ Dly\ Auto\ VMT\ Chg_i^{VA,Pre} - Future\ Dly\ Auto\ VMT\ Chg_i^{VA,Post}$

12. Repeat Steps #1-#3 for other employment growth scenarios, and determine the low, medium and high estimates for the net daily auto VMT avoided.

Estimate daily truck VMT added in future year (2050) due to e-commerce growth for each employment growth scenario.

13. For a given employment growth scenario, estimate future year (2050) daily e-commerce delivery van and truck VMT added over base year (2023) at the Virginia MSA level. An annual to daily conversion factor of 300 was used instead of 365 (typical number of days in a year) to represent peak daily demand for e-commerce goods.
$Future\ Dly\ Dlvry\ Van\ VMT\ Chg_i^{VA}$
$= Future\ E\text{-}com\ Tons\ Chg_i^{VA} \times (1 + Return\%^{Online}) \times AvgTripLen^{Van} \times E\text{-}com\ Mode\%^{Van} / Payload^{Van} \times 300$

$Future\ Dly\ Dlvry\ Trk\ VMT\ Chg_i^{VA}$
$= Future\ E\text{-}com\ Tons\ Chg_i^{VA} \times (1 + Return\%^{Online}) \times AvgTripLen^{Trk} \times E\text{-}com\ Mode\%^{Trk} / Payload^{Trk} \times 30$

$AvgTripLen^{Van} = AvgTripLen^{Trk} = Ann\ Mileage^{Trk\ Or\ Van} / \#\ of\ Stops\ per\ Tour^{Trk\ Or\ Van} \times 300$

Where:

- $Ann\ Mileage^{Trk\ Or\ Van}$: Annual mileage for delivery truck or van, which is assumed as 30,000 miles[28]
- $\#\ of\ Stops\ per\ Tour^{Trk\ Or\ Va}$: Assumed as 100 stops for large MSA (over 1 million people), 50 stops for small MSA (less than 1 million people), 25 stops for non-MSA based on World Bank study[29]
- $AvgTripLen^{Van} = AvgTripLen^{Trk}$: Estimated average trip length per delivery stop, with the lowest value of 1 mile for large MSA (over 1 million people), 2 miles for small MSA (less than 1 million people), 4 miles for non-MSA
- $Payload^{Van}$: Assumed as 4,000 pounds per delivery van[30]
- $Payload^{Trk}$: Assumed as 8,000 pounds per delivery truck[31]

[23]National Retail Federation, 2024, Consumer Returns in the Retail Industry.

[24]National Retail Federation, 2024, Consumer Returns in the Retail Industry.

[25]Oak Ridge National Laboratory (ORNL), 2022, National Household Travel Survey (NHTS), Average trip length for shopping trip purposes by MSA size.

[26]Vehicle Travel Information System (VTRIS), 2010-2014 (5-Year), W-3 Tables for Virginia, Average Gross Weight and Payload (lbs) for Trucks.

[27]McKinsey & Company, 2016, Parcel delivery: The future of last mile.

[28]ICF, 2019, Comparison of Medium- and Heavy-Duty Technologies in California, Final Report Prepared for California Electric Transportation Coalition and Natural Resources Defense Council.

[29]The World Bank, 2019, Facilitating Trade and Logistics for E-Commerce: Building Blocks, Challenges and Ways Forward.

[30]Vehicle Travel Information System (VTRIS), 2010-2014 (5-Year), W-3 Tables for Virginia, Average Gross Weight and Payload (lbs) for Trucks.

[31]Vehicle Travel Information System (VTRIS), 2010-2014 (5-Year), W-3 Tables for Virginia, Average Gross Weight and Payload (lbs) for Trucks.

- *E-com Mode%*^{Van}: mode share of delivery van assumed as 20 percent for large MSA (over 1 million people), 10 percent for small MSA (less than 1 million people), and 5 percent for non-MSA
- *E-com Mode%*^{Trk}: mode share of delivery van assumed as 70 percent for large MSA (over 1 million people), 85 percent for small MSA (less than 1 million people), and 95 percent for non-MSA
- NOTE: The remaining mode share comes from auto-based store pick up and drone delivery mentioned in Step #3.

14. Repeat Step #5 for other employment growth scenarios, and determine the low, medium and high estimates for the daily e-commerce delivery van and truck VMT added.

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

Estimate daily truck VMT added in future year (2050) due to 3D printing or additive manufacturing growth for each employment growth scenario.

15. For a given employment growth scenario, determine the future year (2050) annual increase in 3D printing or manufacturing sales over the base year (2023).

$$\begin{aligned} &\textit{Future 3DP Sales Chg}_j^{VA} \\ &= \textit{Future Output}_{j,GM}^{VA} \times \textit{Future Mfg Output Share}_j^{VA} \times \textit{Future 3DP Sales \%}_j^{VA} \\ &- \textit{Base Output}_{GM}^{VA} \times \textit{Base Mfg Output Share}_j^{VA} \times \textit{Base 3DP Sales \%}_j^{VA} \end{aligned}$$

Where:

- *Future Mfg Output Share*$_j^{VA}$: Future year (2050) manufacturing sector total sales share of out of goods movement dependent sectors total output in Virginia geography *j* based on *Macrotrend #6* and under a given employment growth scenario
- *Future 3DP Sales %*$_j^{VA}$: Future year (2050) 3D printing or additive manufacturing sales share of out of total manufacturing sector sales in Virginia geography *j* based on *Macrotrend #6* and under a given employment growth scenario
- *Base Mfg Output Share*$_j^{VA}$: Base year (2023) manufacturing sector total sales share of out of goods movement dependent sectors total output in Virginia geography *j* based on *Macrotrend #6*
- *Base 3DP Sales %*$_j^{VA}$: Base year (2023) 3D printing or additive manufacturing sales share of out of total manufacturing sector sales in Virginia geography *j* based on *Macrotrend #6*
- *j*: index for Virginia geographies that include statewide and metropolitan statistical areas (MSAs) of Blacksburg-Christiansburg-Radford, Charlottesville, Harrisonburg, Lynchburg, Richmond, Roanoke, Staunton-Stuarts Draft, and Virginia parts of Kingsport-Bristol, Virginia Beach-Chesapeake-Norfolk, Washington-Arlington-Alexandria and Winchester.

16. Convert the increase in annual 3D printing or additive manufacturing sales in Step #7 to annual tons of 3D printing or additive manufacturing using average value per ton for a 3D printing commodity. Use US BTS and FHWA's Freight Analysis Framework Version 5.6 (FAF v5.6) database,[32] based on which the value per ton for a shortlist of 3D printing or additive manufacturing related commodities – namely, articles-base metal, electronics, machinery, misc. mfg. prods., motorized vehicles, nonmetal min. prods., plastics/rubber, precision instruments, textiles/leather and transport equip. - traveling within Virginia was estimated as $2,029 per ton.

$$\textit{Future 3DP Tons Chg}_j^{VA} = \textit{Future 3DP Sales Chg}_j^{VA} \times \textit{ValPerTon}_{3DP}^{FAF}$$

Where:

- *ValPerTon*$_{3DP}^{FAF}$: FAF v5.6 based value per ton for B2C e-commerce commodity

17. The annual tons of 3D printing or additive manufacturing estimated will shift from large long-haul and drayage trucks to large and small short-haul trucks due to localization of manufacturing. For a given employment growth scenario, estimate future year (2050) daily long-haul and drayage truck VMT avoided and daily regional short-haul truck VMT added over base year (2023) at the Virginia MSA level. An annual to daily conversion factor of 300 was used instead of 365 (typical number of days in a year) to represent peak daily demand for 3D printed goods.

[32] U.S. Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA), 2023, Freight Analysis Framework Version 5.6 (FAF v5.6), Tonnage and Value Summary for Commodities.

Future Dly LLH Trk VMT Dec$_j^{VA}$
$= \sum_i \text{Future 3DP Tons Chg}_i^{VA} \times \text{LLH Trk Tons \%}_i^{VA} \times \text{LLH Trk VMT per Trk Ton}_i^{VA} / 300$

Future Dly Dray Trk VMT Dec$_j^{VA}$
$= \sum_i \text{Future 3DP Tons Chg}_i^{VA} \times \text{Dray Trk Tons \%}_i^{VA} \times \text{Dray Trk VMT per Trk Ton}_i^{VA} / 300$

Future Dly LSH Trk VMT Inc$_j^{VA}$
$= \sum_i \text{Future 3DP Tons Chg}_i^{VA} \times \text{LSH Trk Tons \%}_i^{VA} \times \text{LSH Trk VMT per Trk Ton}_i^{VA} / 300$

Future Dly SSH Trk VMT Inc$_j^{VA}$
$= \sum_i \text{Future 3DP Tons Chg}_i^{VA} \times \text{SSH Trk Tons \%}_i^{VA} \times \text{SSH Trk VMT per Trk Ton}_i^{VA} / 300$

Where:

- *LLH Trk*: Class 8 (large) long-haul truck created by combining statistics for FHWA truck classes 9, 10, 11, 12 and 13 and multiplying by long-haul share of 45.80 percent for this truck type[33]
- *Dray Trk*: Class 8 (large) drayage truck created by combining statistics for FHWA truck classes 9, 10, 11, 12 and 13 and multiplying by short-haul share of 54.20 percent for this truck type, and a 50 percent adjustment factor for drayage share out of drayage and short-haul total.[34] This is used only in MSAs with port access, e.g., Virginia Beach-Chesapeake-Norfolk MSA.
- *LSH Trk*: Class 8 (large) short-haul truck created by combining statistics for FHWA truck classes 9, 10, 11, 12 and 13 and multiplying by short-haul share of 54.20 percent for this truck type, and a 50 percent adjustment factor for short-haul share out of drayage and short-haul total.[35]
- *SSH Trk*: Class 6/7 (small) regional short-haul truck created by combining statistics for FHWA truck classes 6 and 7 and multiplying by short-haul share of 26.80 percent for this truck type[36]
- *LLH Trk Tons %*$_i^{VA}$: Tonnage share of VA geography *j* out of state total for Class 8 long-haul truck multiplied by global sourcing split of 52.4 percent[37] avoided, this is a negative percentage value
- *Dray Trk Tons %*$_i^{VA}$: Tonnage share of port access MSA (e.g., Virginia Beach-Chesapeake-Norfolk MSA only) for Class 8 drayage truck multiplied by global sourcing split of 2.6 percent[38] avoided, this is a negative percentage value
- *LSH Trk Tons %*$_i^{VA}$: Tonnage share of Class 8 short-haul truck multiplied by local sourcing split of 3.12[39] percent added, this is a positive percentage value
- *SSH Trk Tons %*$_i^{VA}$: Tonnage share of Class 6/7 regional short-haul truck multiplied by local sourcing split of 51.92 percent[40] added, this is a positive percentage value
- Statistics combined for LLH Trk, Dray Trk, LSH Trk and SSH Trk include: tonnage share and truck VMT per ton metrics for constituent FHWA classes

18. Repeat Step #7-#9 for other employment growth scenarios, and determine the low, medium and high estimates for the daily 3D printing or additive manufacturing related truck VMT changes.

[33] U.S. Department of Commerce, Bureau of the Census, 2002 Vehicle Inventory and Use Survey (VIUS), Short-Haul (less than equal to 100 miles) and Long-Haul (more than 100 miles) Shares by Weight Class of Truck.

[34] U.S. Department of Commerce, Bureau of the Census, 2002 Vehicle Inventory and Use Survey (VIUS), Short-Haul (less than equal to 100 miles) and Long-Haul (more than 100 miles) Shares by Weight Class of Truck.

[35] U.S. Department of Commerce, Bureau of the Census, 2002 Vehicle Inventory and Use Survey (VIUS), Short-Haul (less than equal to 100 miles) and Long-Haul (more than 100 miles) Shares by Weight Class of Truck.

[36] U.S. Department of Commerce, Bureau of the Census, 2002 Vehicle Inventory and Use Survey (VIUS), Short-Haul (less than equal to 100 miles) and Long-Haul (more than 100 miles) Shares by Weight Class of Truck.

[37] U.S. Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA), 2023, Freight Analysis Framework Version 5.6 (FAF v5.6), Tonnage and Value Summary for Commodities.

[38] U.S. Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA), 2023, Freight Analysis Framework Version 5.6 (FAF v5.6), Tonnage and Value Summary for Commodities.

[39] U.S. Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA), 2023, Freight Analysis Framework Version 5.6 (FAF v5.6), Tonnage and Value Summary for Commodities.

[40] U.S. Bureau of Transportation Statistics (BTS) and Federal Highway Administration (FHWA), 2023, Freight Analysis Framework Version 5.6 (FAF v5.6), Tonnage and Value Summary for Commodities.

Estimate daily truck VMT added in future year (2050) due to productivity growth for each employment growth scenario.

19. Under a given employment growth scenario, estimate future year (2050) increase in VMT due to productivity growth in goods movement dependent sectors by applying productivity growth factors to the future year (2050) baseline VMT by Virginia MSA, which in turn is calculated by applying employment growth factors only to base year (2023) VMT by Virginia MSA.
20. Repeat Step #11 for other employment growth scenarios, and determine the low, medium and high estimates for the productivity growth factors related truck VMT changes.

Table 3.3.3-1: Statewide E-Commerce Growth Related Auto VMT Avoided Forecast (2050)

Metric	Low Scenario	Medium Scenario	High Scenario
VMT Avoided Forecast (2050)	60,900	60,900	83,400

Table 3.3.3-2: E-Commerce Growth Related Truck VMT Added Forecast (2050)
[NOTE: All "Medium" Truck Type Changes, No Changes to "Heavy" Truck Type .]

Metric	Low Scenario	Medium Scenario	High Scenario
Daily Truck VMT Added in mill. (2050)	0.0030	0.0030	0.0042
Share of Baseline Truck VMT (2050)	0.024%	0.023%	0.026%

Table 3.3.3-3: 3D Printing Growth Related "Heavy" Truck VMT Avoided Forecast (2050)

Metric	Low Scenario	Medium Scenario	High Scenario
Medium-duty Trucks VMT Added			
Daily Truck VMT Added in mill. (2050)	0.0201	0.0204	0.0224
Share of Baseline Truck VMT (2050)	0.236%	0.229%	0.204%
Heavy-duty Trucks VMT Avoided			
Daily Truck VMT Added in mill. (2050)	0.0436	0.0442	0.0485
Share of Baseline Truck VMT (2050)	1.073%	1.040%	0.922%

Table 3.3.3-4: Productivity Growth Related to Medium- and Heavy-duty Truck VMT Added Forecast (2050)

Metric	Low Scenario	Medium Scenario	High Scenario
Medium-duty Trucks			
Daily Truck VMT Added in mill. (2050)	2.01	1.74	1.76
Share of Baseline Truck VMT (2050)	23.5%	19.6%	16%
Heavy-duty Trucks			
Daily Truck VMT Added in mill. (2050)	0.92	0.8	0.81
Share of Baseline Truck VMT (2050)	22.7%	18.7%	15.3%

Calculate the combined effect of the Macrotrends on vehicle miles traveled

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

1. Compile base data (typical workday), including home-based work (HBW) auto trips and HBW auto VMT from Replica (Thursday, Spring 2022), estimated telework employment from section 3.1.8., and daily DVMT from VDOT.
2. Calculate HBW commute VMT per job:
   $vmt\_per\_job\_day = HBW\_auto\_VMT / jobs_{2022,g}$
3. Define telework frequency and annualization:
   $WFH\_days\_per\_year = (261/5) \times 1.6$[1]
4. Obtain the number of workers teleworking in 2050 by scenario from Step 1 (section 3.1.8):
   WF_jobs_{2050s}
5. Estimate the raw annual HBW auto VMT reduction for each scenario s:
   $RawVMT_s = WF\_jobs_{2050s} \times vmt\_per\_job\_day \times WFH\_days\_per\_year$
6. Apply the rebound (non-work) discount to obtain the net annual reduction:
   $NetVMT_{c,s} = RawVMT_s \times (1 - 0.30)$
7. Calculate the percent reduction in annual commute VMT for scenario *s*:
   $\%\Delta\ VMT^{commute}_s = NetVMT_s / (HBW\_auto\_VMT \times 261)$
8. Calculate the percent reduction in total annual VMT for each county *c* and scenario *s*:
   $\%\Delta\ VMT^{total}_s = NetVMT_s / (DVMT \times 365)$

Where:

- $HBW\_auto\_VMT_c$ is the typical-workday home-based work auto VMT from Replica (auto driver + passenger).
- $jobs_{2022}$ is the total employment estimated in Step 1 (section 3.1.8) employment totals.
- *WFH_days_per_year* converts average weekly telework days to annual workdays using 261 weekdays/year and a 5-day workweek.
- WF_jobs_{2050s} is the number of workers teleworking in 2050 under scenario s (Step 1 output).
- $RawVMT_s$ is the gross annual commute VMT avoided before rebound.
- $NetVMT_s$ is the rebound-adjusted annual commute VMT avoided (rebound factor = 30%).
- $\%\Delta\ VMT^{commute}_s$ is the net percent reduction relative to annual commute VMT (HBW_auto_VMT × 261).
- $\%\Delta\ VMT^{total}_s$ is the net percent reduction relative to all-purpose annual VMT (DVMT × 365).

21. Combine the independent effects of each macrotrend on VMT (calculation steps # 7, # 8, # 16, and # 21) by multiplying the independent effects of each macrotrend using the following equation:

    $Total\ ImpactVMT = VMT_{start} \times (1 + MT_7) \times (1 + MT_{2\ 3\ 4}) \times (1 + MT_5) \times (1 + MT_6) \times (1 + MT_4) \times (1 + MT_8)$

22. Combine the macrotrend effects on Truck VMT (calculation steps #14 and #16) to calculate the truck index using the following equation:

    $Truck\ Index =$
    $(1 + \%\Delta VMT_{M-5}) * (1 + \%\Delta VMT_{M-6}) * DVMT_M + (1 + \%\Delta VMT_{H-5}) * (1 + \%\Delta VMT_{H-6}) * DVMT_H / DVMT_M + DVMT_H$

[1] "Working from home 2025 – Five key facts" Stanford Institute for Economic Policy Research)

Where:

- $\%\Delta VMT_{M-5}$: Percent change in medium truck VMT due to growth in E-commerce accounting for commercial drone delivery services
- $\%\Delta VMT_{M-6}$: Percent change in medium truck VMT due to production automation including 3D printing
- $\%\Delta VMT_{H-5}$: Percent change in heavy truck VMT due to growth in E-commerce accounting for commercial drone delivery services
- $\%\Delta VMT_{H-6}$: Percent change in heavy truck VMT due to production automation including 3D printing
- $DVMT_{M}$: Daily VMT of medium trucks
- $DVMT_{H}$: Daily VMT of heavy trucks

Step 3: Impact of VTrans Macrotrends on CTB Goal C in the Year 2050

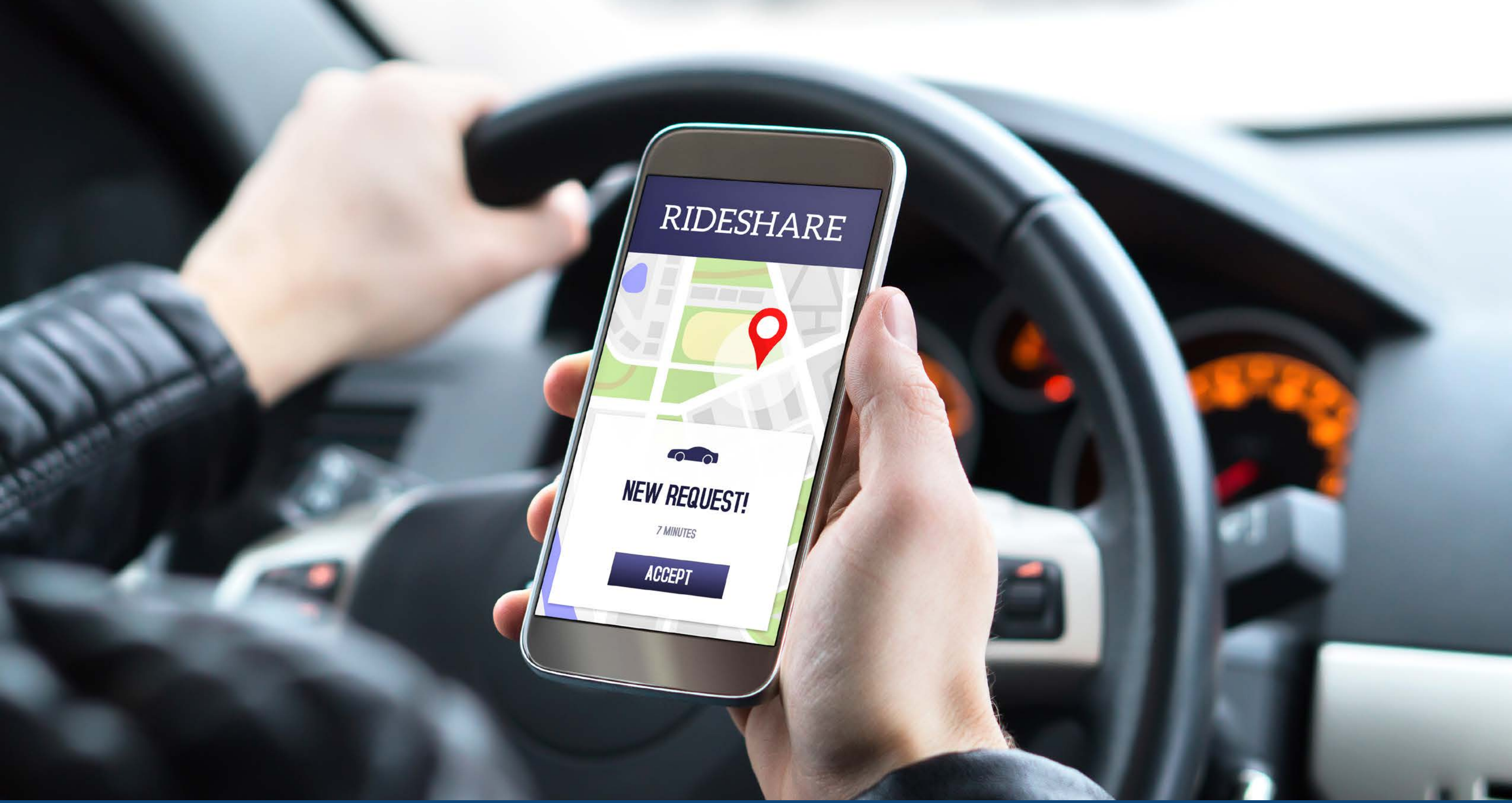
The results of calculation step # 22 are included in Table 3.3.1-7 and should be interpreted as follows:

- **Low estimate:** Overall number of vehicle miles traveled in Virginia is estimated to increase by 1 percent and the truck VMT is expected to decrease by 16 percent compared to the Business-as-Usual (where VTrans Macrotrends have no impact).
- **Medium estimate:** Medium-impact Scenario: Overall number of vehicle miles traveled in Virginia is estimated to increase by 3 percent and the truck VMT is expected to decrease by 19 percent compared to the Business-as-Usual (where VTrans Macrotrends have no impact).
- **High estimate:** Overall number of vehicle miles traveled in Virginia is estimated to increase by 8 percent and the truck VMT is expected to decrease by 23 percent compared to the Business-as-Usual (where VTrans Macrotrends have no impact).

Table 3.3.3-5. Estimated Impact of VTrans Macrotrends on CTB Goal C in Year 2050

CTB Goal	Metric for CTB Goal	Low Estimate	Medium Estimate	High Estimate
Goal C: Economic Competitiveness through Travel Time Reliability.	Vehicle Miles Traveled Index (All)	1.01	1.03	1.08
	Vehicle Miles Traveled Index (Truck Only)	1.16	1.19	1.23

Where 1.0 is 2050 business-as-usual scenario where VTrans Macrotrends have no impacts.



3.3.4. Impact of Step 1 Macrotrends on CTB Goal D Metrics

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 Goal D: Inter-Connected Systems and Services.

Data Sources:

- Percentage of VMT switchable to TNC at the state level and the construction district level.
- Percentage of VMT switchable to micromobility at the state level and the construction district level.

Calculations:

Calculations to measure change in share of VMT switchable to shared mobility in future year (2050) rely on outputs related to the following macrotrends included in Section 3.1, Step 1. The calculation relative to the baseline is as follows.

1. Calculate the shared mobility index (ridesourcing), which represents the change in share of VMT switchable to ridesourcing compared to 2022 baseline, using the following equation.

   $$\textit{shared mobility index (Ridesourcing)} = 1 + (\%\ VMT_s \textit{ switchable to TNC})$$

2. Calculate the shared mobility index (micromobility), which represents the change in share of VMT switchable to micromobility compared to 2022 baseline, using the following equation.

   $$\textit{shared mobility index (Micromobility)} = 1 + (\%\ VMT_s \textit{ switchable to Micromobility})$$

3. Calculate the shared mobility index (micromobility), which represents the change in share of VMT switchable to shared mobility compared to 2022 baseline, using the following equation.

   $$\textit{shared mobility index} = 1 + (\%\ VMT_s \textit{ switchable to TNC} + \%\ VMT_s \textit{ switchable to Micromobility})$$

   Where:
   s = Scenario (Low/Med/High)

Step 3: Impact of VTrans Macrotrends on CTB Goal D in Year 2050

The results of the change in share of VMT switchable to ridesourcing, micromobility, and shared mobility calculations are included in Table 3.3.2-1. Statewide results should be interpreted as follows:

- **Low estimate:** The change in share of VMT switchable to ridesourcing, micromobility, and shared mobility are estimate to be 1.5 percent, 0.05 percent, and 2 percent higher than the 2050 no-build scenario, respectively.
- **Medium estimate:** The change in share of VMT switchable to ridesourcing, micromobility, and shared mobility are estimated to be 4 percent, 0.07 percent, and 4 percent higher than the 2050 no-build scenario, respectively.
- **High estimate:** The change in share of VMT switchable to ridesourcing, micromobility, and shared mobility are estimated to be 5.8 percent, 0.1 percent, and 6 percent higher than the 2050 no-build scenario, respectively.

Table 3.3.4-1: Change in share of VMT switchable to shared mobility

CTB Goal	Metric for CTB Goal	Low Estimate	Medium Estimate	High Estimate
Goal D: Inter-Connected Systems and Services.	Shared Mobility Index (Ridesourcing and Micromobility Combined)	1.02	1.05	1.08
	Shared Mobility Index (Ridesourcing Only)	1.01	1.05	1.07
	Shared Mobility Index (Micromobility Only)	1.0005	1.0009	1.001

Limitations:

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.

3.3.5. Impact of Step 1 Macrotrends on CTB Goal E Metrics

Description: As outlined in Section 3.2, estimated change in tailpipe emissions for the future year (2050) is used as the metric to assess the impact of the VTrans Macrotrends (outlined in Section 3.1) on Goal E: Environmental Stewardship.

Significance: Tailpipe emissions can impact CTB Goal E.[1]

Data Sources:

- Long-term VMT forecasts: Federal Highway Administration[2]
- VMT in Virginia in 2022 by functional system: Federal Highway Administration[3]
- VMT in Virginia in 2022 by vehicle type: VDOT[4]
- Forecasted shares of vehicles in 2050 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[5]
- Emissions tonnage by vehicle weight class: EPA[6]
- Change in emissions due to electrification: Energy Innovations[7]
- 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

[1] U.S. Environmental Protection Agency (2020). Smog, Soot, and Other Air Pollution from Transportation. Last updated August 7, 2025.

[2] Federal Highway Administration (2024). FHWA Forecasts of Vehicle Miles Traveled (VMT): Spring 2024

[3] Federal Highway Administration (2020). "Functional System Travel – 2022 Annual Vehicle-Miles." Highway Statistics 2022.

[4] VDOT, 2022, Vehicle miles traveled (VMT) by Physical Jurisdiction and by Federal Vehicle Class across All Roads.

[5] U.S. Environmental Protection Agency (2024). "Table 2.1. Production, Estimated Real-World CO2, and Fuel Economy for Model Year 1975–2024."2019 EPA Automotive Trends Report.

[6] U.S. Environmental Protection Agency (2020). National Emissions Inventory Data - Virginia

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

Calculations:

These calculations rely on research conducted for Step 1. The following six (6) macrotrends are expected to influence Tailpipe Emissions. 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 (Micromobility 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..

   Δlight vehicles = ΔVMT from Shared Mobility × 2022 DVMT all classes/2022 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.
   - *2022 DVMT all classes* is the daily VMT in 2022 from all vehicle classes in Virginia. This is used to scale the change in VMT to make it account for light vehicles only.
   - *2022 DVMT light* is the daily VMT in 2022 from motorcycles, passenger cars, and two-axle 4-tire single unit vehicles.
   - Utilize calculation in Section 3.3.1 to estimate light vehicle VMT avoided due to e-commerce.
   - Utilize calculation in Section 3.3.1 to estimate the increase in medium and heavy trucks VMT in the future year 2050 due to growth in e-commerce.

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

3. Utilize calculations in Section 3.3.1 to estimate light vehicle VMT avoided due to e-commerce,
4. Utilize calculations in Section 3.3.1 to estimate the increase in medium and heavy trucks VMT in the future year 2050 due to growth in e-commerce.

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

5. Utilize calculation calculations in Section 3.3.1 to 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 calculation in 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.
   Combined effect $= \prod_{m \in M} (1 + \textit{effect on } VMT_m)$

   Where:
   - m is a Macrotrend out of all applicable macrotrends M.
   - *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 3.3.5-1: 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	0.7%	2.2%	8.3%						
Adoption of Electric Vehicles									
Growth in Shared Mobility	-0.05%	- 0.1%	-0.14%						
Growth in E-commerce	-0.02%	-0.02%	-0.03%	0.03%	0.0%	0.0%	0.0%	0.0%	0.0%
Greater Automation of Automation and Services (due to increased productivity)				16.0%	19.6%	23.5%	15.3%	18.7%	22.7%
Greater Automation of Automation and Services (due to avoided shopping trips)				0.2%	0.2%	0.2%	-1.1%	-1.0%	-0.9%
Increase in Workplace Flexibility	-0.7%	-0.7%	-0.9%						
Net Impact of Macrotrends	0.001%	1.3%	7.2%	16.2%	19.9%	23.81%	14.2%	17.7%	21.7%

8. Calculate tons per mile by converting annual emission tonnage to daily emission tonnage and dividing by daily VMT called "Per VMT" in Table 3.3.5-2.

Table 3.3.5-2: Emissions by Vehicle Weight Class

Vehicle type	Emission tonnage		
	Annual	Daily	Per VMT
Heavy-duty Vehicles	9,454,162	25,902	0.002379
Medium-duty Vehicles	Not available	Not available	0.001414
Light-duty Vehicles	31,619,377	86,628	0.000449

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 2050. Data for fuel efficiency is from the Environmental Protection Agency's (EPA) real-world fuel economy between 1990 and 2024 and extrapolated to 2050 using linear trends. The resulting decrease in fuel consumption (called "ICE emissions reduction") is 20 percent.

10. Estimate base year (2022) tailpipe emissions in tons per mile utilizing annual emission tonnage by vehicle weight class.

    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. Calculated 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 2050 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 2022 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 × tons per mile × VMT × (EV share × (1–EV effect) + (1–EV share) × (1-ICE emissions reduction))

    Where:
    - *combined effect* was calculated for each scenario and vehicle type from Table 3.3.5-1 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 2022 VMT by federal vehicle class from VDOT for all Virginia roads.
    - *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 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 3.3.5-3 and should be interpreted as follows:

- Low-impact Scenario: Tailpipe emissions are estimated to decrease by 13 percent over the 2050 no-build scenario (absence of VTrans Macrotrends (Step 1)
- Medium-impact Scenario: Tailpipe emissions are estimated to decrease by 33 percent over the 2050 no-build scenario (absence of VTrans Macrotrends (Step 1)
- High-impact scenario: Tailpipe emissions are estimated to decrease by 58 percent over the 2050 no-build scenario (absence of VTrans Macrotrends (Step 1)

Table 3.3.5-3: Estimated Impact of VTrans Macrotrends on CTB Goal E in Year 2050

CTB Goal	Metric for CTB Goal	Low Estimate	Medium Estimate	High Estimate
Goal E: Environmental Stewardship.	Tailpipe Emissions Index	0.864	0.668	0.423

Where 1.0 is 2050 business-as-usual scenario where VTrans Macrotrends have no impact.

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

OIPI shall develop and update the VTrans Long-term Risk & Opportunity Register (the Risk Register) based on feedback and direction from the CTB and other stakeholders. At minimum, the Risk Register shall be based on reliable sources reflecting the state of the practice to allow for quantification of impacts of VTrans Macrotrends listed in Step 1 of the process.

The VTrans Long-term Risk & Opportunity shall allow for systematic and methodical identification of risks[1] and opportunities.[2] It shall also take 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.

Table 3.4-1 lists risks and opportunities identified based on the 2021 Update.

Table 3.4-1: VTrans 2021 Long-term Risk & Opportunity Register

Macrotrend	Characterization	Description
		1. A large number of the state's roadways are at risk of flooding 2. Several unknown and unquantified flooding risks are present 3. Impacts of increased flooding risk are disproportionately higher for certain geographic areas and populations
		4. Proactively eliminate or mitigate identified flooding risks 5. Increase the state's preparedness to address other macrotrends associated with climate change megatrend

Uncertainty with negative impacts on CTB Goals in Step 3

Uncertainty with a positive impact on CTB Goals in Step 3

[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.

Macrotrend	Characterization	Description
	⚠	6. Greater wear-and-tear on the transportation system due to increased vehicle miles traveled (VMT) and increase in average vehicle weight
	⚠	7. Improve the state's ability to manage a transportation system with a high number of highly autonomous vehicles 8. Maximize safety benefits offered by highly autonomous vehicles, especially those with Automated Driving System
	☀	9. Higher vehicle miles traveled (VMT) for each unit of economic activity compared to the present fleet
	☀	10. Minimize environmental impacts of the transportation system development
	⚠	11. Increased curb access conflicts in urbanized areas
	⚠	12. Projected growth in shared mobility (micromobility and TNC/ridesourcing) does not provide measurable transportation system benefits 13. Benefits of growth in shared mobility are not equally accessible by all areas and population segments
	☀	14. Utilize shared mobility services to improve accessibility 15. Improve the state's ability to manage a transportation system with a high number of shared mobility vehicles
	☀	16. Proactively eliminate or mitigate transportation impacts associated with e-commerce including those related to large warehouse and distribution centers
	☀	17. Improve state's ability to proactively manage transportation impacts associated with greater automation of production and services
	☀	18. Maximize utilization of workplace flexibility for telework capable jobs
	⚠	19. Transportation system and services are unable to meet mobility needs of Virginians age 65 and older

⚠ Uncertainty with negative impacts on CTB Goals in Step 3

☀ Uncertainty with a positive impact on CTB Goals in Step 3

6.4.1 Interpretation and Usage of the VTrans Long-term Risk & Opportunity Register

- The methodology outlined in the Technical Guide: Development and Monitoring of VTrans Long-term Risk & Opportunity Register, shall direct the development and monitoring of VTrans Long-term Risks and Opportunities and may continue to evolve and improve based upon advances in technology, data collection, and reporting tools, and 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 Board for review and approval.
- OIPI, VDOT, an DRPT shall undertake coordinated actions to minimize long-term risks and maximize benefits of long-term opportunities identified in the 2021 VTrans Long-term Risk & Opportunity Register.
- Outputs of VTrans policies, including, but not limited to, VTrans Vision, Goals, Objectives, and Guiding Principles, VTrans Mid-term Needs, and VTrans Risks and Opportunities as well as VTrans concepts including, but not limited to, Equity Emphasis Areas, Activity Centers, market adoption curves for electric and automated vehicles, and impacts of VTrans Macrotrends shall be utilized by OIPI, VDOT and DRPT for statewide planning activities, and developing or modifying practices and Board policies.

3.5. Step 5: Track Macrotrends

OIPI shall provide updates to the CTB on the VTrans Mega- and Macrotrends and any changes to items in the 2021 Long-term Risk & Opportunity Register once per calendar year based on a monitoring of the macrotrends and the Trend Trackers identified in Table 3.5-1.

Table 3.5-1: VTrans Trend Trackers

VTrans Macrotrend	VTrans Trend Trackers
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 ▪ Annual cost of transportation repair due to flooding events
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[1] ▪ Market Penetration of Highly Autonomous (Levels 3 and 4) Vehicles[1] ▪ Attitude and Preferences for Adoption of Highly Autonomous (Levels 3 and 4)[1] Vehicles
3. Adoption of Electric Vehicles	▪ Number of Electric Vehicles ▪ Market Penetration of Electric Vehicles ▪ Attitude and Preferences for Adoption of Electric Vehicles[1] ▪ Transportation Revenue by Revenue Source
4. Growth in Shared Mobility	▪ Access to Shared Mobility Services[1] ▪ Utilization of Shared Mobility Services by Type[1]
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
6. Greater Automation of Production and Serices	▪ Number of short-range drone deliveries ▪ Number of long-range drone deliveries
7. Growth of Professional Services Industry	▪ Share of Professional Services Industry Jobs ▪ Number of STEM Jobs
8. Increase in Workplace Flexibility	▪ Number of Workers with Workplace Flexibility[1] ▪ Utilization of Workplace Flexibility[1]
9. Growth of the Age 65+ Cohort	▪ Number of Virginians with Age 65 or higher ▪ Share of Age 65+ Cohort
10. Population and Employment Shift	▪ VTrans Land Use Vitality (LUV) Index ▪ Population ▪ Employment ▪ Income

[1] OIPI shall conduct a biennial statistically valid survey to measure these trend trackers.

APPENDIX 1: METHODOLOGY TO ASSIGN EXPOSURE VALUES TO ROADWAY SEGMENTS

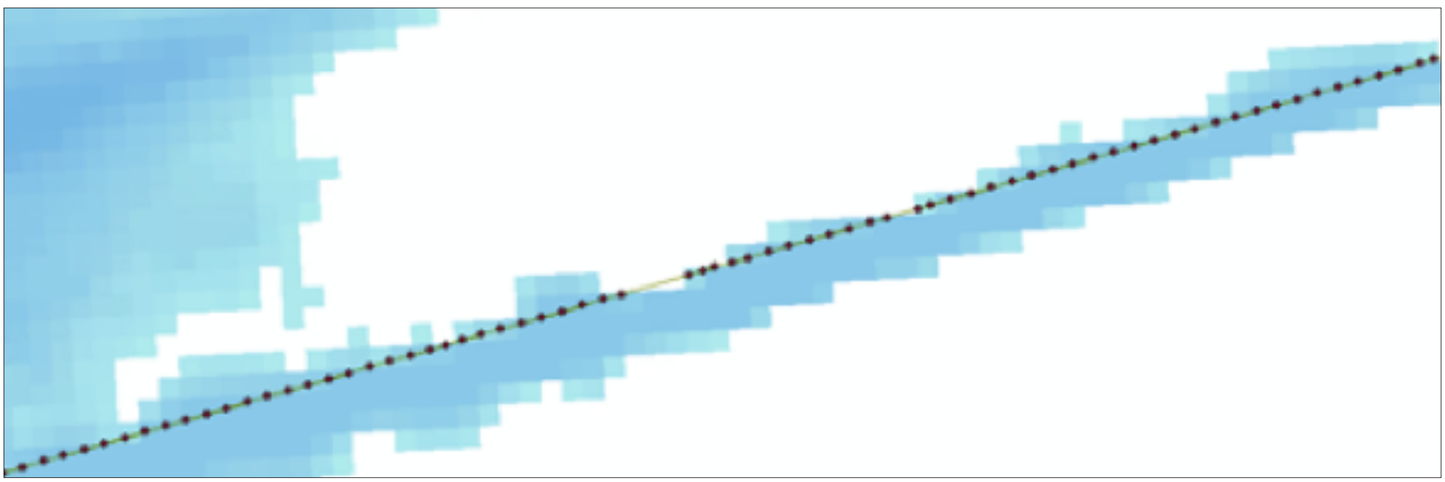
Exposure Assessment Methodology

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 Appendix 3-1).
  5. Summarize the result to obtain the maximum depth for each roadway segment in VDOT LRS 19.1.

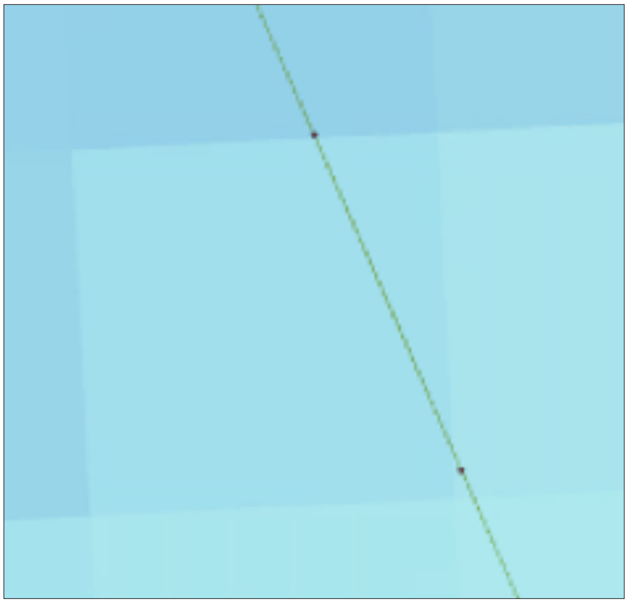
Figure Appendix 1-1: Sampling of Sea Level Rise Data



- 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 Appendix 3-2).
  5. Summarize the result to obtain the maximum depth for each roadway segment in VDOT LRS 19.1.

Figure Appendix 1-2: 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 Appendix 3-1 and 3-2). 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 2.

2. Exposed to a historical flood event as outlined in Appendix 1.

- 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 2: SOCIO-DEMOGRAPHIC TRENDS RELATED ASSUMPTIONS AND OPPORTUNITIES FOR CONTINUOUS IMPROVEMENT

Table Appendix 2-1: 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

Table Appendix 2-2: Jurisdictions Associated with each Modified Planning District Commission

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 3: STANDARD OCCUPATIONAL CLASSIFICATION (SOC) OCCUPATIONS WITH 5 OR ABOVE AUTOMATION EXPOSURE RATING (AER)

SOC Code	SOC Title	AER
11-3051	Industrial Production Managers	5
11-3051	Biomass Power Plant Managers	5
11-9013	Farmers, Ranchers, and Other Agricultural Managers	5
11-9051	Food Service Managers	6
11-9121	Clinical Research Coordinators	5
13-1022	Wholesale and Retail Buyers, Except Farm Products	5
13-1031	Claims Adjusters, Examiners, and Investigators	6
13-1032	Insurance Appraisers, Auto Damage	6
13-1041	Compliance Officers	6
13-1041	Government Property Inspectors and Investigators	5
13-1041	Customs Brokers	5
13-1074	Farm Labor Contractors	7
13-1199	Online Merchants	5
13-2023	Appraisers and Assessors of Real Estate	5
13-2031	Budget Analysts	6
13-2071	Credit Counselors	5
13-2081	Tax Examiners and Collectors, and Revenue Agents	5
13-2082	Tax Preparers	5
15-1211	Computer Systems Analysts	5
15-1231	Computer Network Support Specialists	5
15-1232	Computer User Support Specialists	5
15-1241	Computer Network Architects	5
15-1242	Database Administrators	5
15-1244	Network and Computer Systems Administrators	5
15-1254	Web Developers	5
15-1299	Geographic Information Systems Technologists and Technicians	5
15-1299	Computer Systems Engineers/ Architects	5
17-1021	Cartographers and Photogrammetrists	6
17-1022	Surveyors	6
17-1022	Geodetic Surveyors	6
17-2121	Marine Engineers and Naval Architects	5
17-2199	Robotics Engineers	5
17-3011	Architectural and Civil Drafters	6
17-3012	Electrical and Electronics Drafters	6
17-3013	Mechanical Drafters	6
17-3021	Aerospace Engineering and Operations Technologists and Technicians	6
17-3022	Civil Engineering Technologists and Technicians	5
17-3023	Electrical and Electronic Engineering Technologists and Technicians	5
17-3024	Electro-Mechanical and Mechatronics Technologists and Technicians	7
17-3024	Robotics Technicians	6
17-3025	Environmental Engineering Technologists and Technicians	6
17-3026	Industrial Engineering Technologists and Technicians	5
17-3026	Nanotechnology Engineering Technologists and Technicians	5
17-3027	Mechanical Engineering Technologists and Technicians	5
17-3027	Automotive Engineering Technicians	7
17-3029	Non-Destructive Testing Specialists	6
17-3029	Photonics Technicians	7
17-3031	Surveying and Mapping Technicians	7
19-1022	Microbiologists	5
19-1042	Medical Scientists, Except Epidemiologists	5
19-2031	Chemists	5
19-4012	Agricultural Technicians	7
19-4012	Precision Agriculture Technicians	5
19-4013	Food Science Technicians	6
19-4021	Biological Technicians	6
19-4031	Chemical Technicians	8
19-4042	Environmental Science and Protection Technicians, Including Health	5
19-4043	Geological Technicians, Except Hydrologic Technicians	7
19-4051	Nuclear Technicians	8
19-4051	Nuclear Monitoring Technicians	5
19-4071	Forest and Conservation Technicians	6
19-4092	Forensic Science Technicians	6
19-4099	Quality Control Analysts	7
19-4099	Remote Sensing Technicians	6
21-1092	Probation Officers and Correctional Treatment Specialists	5
23-1012	Judicial Law Clerks	6
23-1021	Administrative Law Judges, Adjudicators, and Hearing Officers	5
23-2011	Paralegals and Legal Assistants	6
23-2093	Title Examiners, Abstractors, and Searchers	6
25-4013	Museum Technicians and Conservators	6
25-4031	Library Technicians	7
27-1012	Craft Artists	7
27-1013	Fine Artists, Including Painters, Sculptors, and Illustrators	6
27-1014	Special Effects Artists and Animators	5
27-1021	Commercial and Industrial Designers	6
27-1023	Floral Designers	6
27-1024	Graphic Designers	5
27-1026	Merchandise Displayers and Window Trimmers	5
27-2011	Actors	5

SOC Code	SOC Title	AER
27-2012	Media Technical Directors/ Managers	6
27-2021	Athletes and Sports Competitors	5
27-2023	Umpires, Referees, and Other Sports Officials	5
27-2031	Dancers	7
27-2042	Musicians and Singers	7
27-3042	Technical Writers	6
27-3043	Poets, Lyricists and Creative Writers	5
27-3091	Interpreters and Translators	5
27-3092	Court Reporters and Simultaneous Captioners	8
27-4011	Audio and Video Technicians	7
27-4012	Broadcast Technicians	6
27-4014	Sound Engineering Technicians	5
27-4021	Photographers	5
27-4031	Camera Operators, Television, Video, and Film	6
29-1011	Chiropractors	5
29-1021	Dentists, General	6
29-1023	Orthodontists	5
29-1024	Prosthodontists	5
29-1051	Pharmacists	6
29-1071	Anesthesiologist Assistants	6
29-1081	Podiatrists	5
29-1124	Radiation Therapists	8
29-1126	Respiratory Therapists	6
29-1131	Veterinarians	5
29-1151	Nurse Anesthetists	5
29-1211	Anesthesiologists	5
29-1222	Physicians, Pathologists	6
29-1224	Radiologists	5
29-1241	Ophthalmologists, Except Pediatric	5

SOC Code	SOC Title	AER
29-1291	Acupuncturists	5
29-1292	Dental Hygienists	6
29-1299	Orthoptists	5
29-2011	Medical and Clinical Laboratory Technologists	7
29-2011	Cytogenetic Technologists	7
29-2011	Cytotechnologists	8
29-2011	Histotechnologists	9
29-2012	Medical and Clinical Laboratory Technicians	7
29-2031	Cardiovascular Technologists and Technicians	7
29-2032	Diagnostic Medical Sonographers	7
29-2033	Nuclear Medicine Technologists	6
29-2034	Radiologic Technologists and Technicians	7
29-2035	Magnetic Resonance Imaging Technologists	6
29-2036	Medical Dosimetrists	6
29-2051	Dietetic Technicians	5
29-2052	Pharmacy Technicians	7
29-2053	Psychiatric Technicians	5
29-2055	Surgical Technologists	6
29-2056	Veterinary Technologists and Technicians	6
29-2057	Ophthalmic Medical Technicians	6
29-2061	Licensed Practical and Licensed Vocational Nurses	5
29-2091	Orthotists and Prosthetists	5
29-2092	Hearing Aid Specialists	5
29-2099	Neurodiagnostic Technologists	5
29-2099	Ophthalmic Medical Technologists	6
29-2099	Patient Representatives	5
29-9091	Athletic Trainers	5
29-9093	Surgical Assistants	6
31-1121	Home Health Aides	6

SOC Code	SOC Title	AER
31-1122	Personal Care Aides	5
31-1131	Nursing Assistants	6
31-1132	Orderlies	8
31-1133	Psychiatric Aides	5
31-2022	Physical Therapist Aides	5
31-9011	Massage Therapists	5
31-9091	Dental Assistants	6
31-9092	Medical Assistants	5
31-9093	Medical Equipment Preparers	8
31-9094	Medical Transcriptionists	7
31-9095	Pharmacy Aides	6
31-9096	Veterinary Assistants and Laboratory Animal Caretakers	6
31-9097	Phlebotomists	6
31-9099	Endoscopy Technicians	7
33-1021	First-Line Supervisors of Firefighting and Prevention Workers	5
33-2011	Firefighters	6
33-2021	Fire Inspectors and Investigators	5
33-2022	Forest Fire Inspectors and Prevention Specialists	6
33-3011	Bailiffs	5
33-3012	Correctional Officers and Jailers	5
33-3021	Detectives and Criminal Investigators	5
33-3021	Police Identification and Records Officers	6
33-3031	Fish and Game Wardens	5
33-3041	Parking Enforcement Workers	7
33-3051	Police and Sheriff's Patrol Officers	5
33-3051	Customs and Border Protection Officers	6
33-3052	Transit and Railroad Police	5
33-9011	Animal Control Workers	6

SOC Code	SOC Title	AER
33-9021	Private Detectives and Investigators	5
33-9031	Gambling Surveillance Officers and Gambling Investigators	6
33-9032	Security Guards	5
33-9091	Crossing Guards and Flaggers	7
33-9092	Lifeguards, Ski Patrol, and Other Recreational Protective Service Workers	6
33-9093	Transportation Security Screeners	8
33-9099	Retail Loss Prevention Specialists	5
35-1011	Chefs and Head Cooks	5
35-1012	First-Line Supervisors of Food Preparation and Serving Workers	6
35-2011	Cooks, Fast Food	7
35-2012	Cooks, Institution and Cafeteria	6
35-2013	Cooks, Private Household	6
35-2014	Cooks, Restaurant	7
35-2015	Cooks, Short Order	7
35-2021	Food Preparation Workers	7
35-3011	Bartenders	5
35-3023	Fast Food and Counter Workers	8
35-3023	Baristas	7
35-3031	Waiters and Waitresses	7
35-3041	Food Servers, Nonrestaurant	7
35-9011	Dining Room and Cafeteria Attendants and Bartender Helpers	7
35-9021	Dishwashers	7
35-9031	Hosts and Hostesses, Restaurant, Lounge, and Coffee Shop	6
37-1011	First-Line Supervisors of Housekeeping and Janitorial Workers	5
37-1012	First-Line Supervisors of Landscaping, Lawn Service, and Groundskeeping Workers	5
37-2011	Janitors and Cleaners, Except Maids and Housekeeping Cleaners	5
37-2012	Maids and Housekeeping Cleaners	7

SOC Code	SOC Title	AER
37-2021	Pest Control Workers	7
37-3011	Landscaping and Groundskeeping Workers	8
37-3012	Pesticide Handlers, Sprayers, and Applicators, Vegetation	7
37-3013	Tree Trimmers and Pruners	8
39-1013	First-Line Supervisors of Gambling Services Workers	7
39-2021	Animal Caretakers	6
39-3011	Gambling Dealers	9
39-3012	Gambling and Sports Book Writers and Runners	8
39-3021	Motion Picture Projectionists	8
39-3031	Ushers, Lobby Attendants, and Ticket Takers	7
39-3091	Amusement and Recreation Attendants	6
39-3092	Costume Attendants	6
39-3093	Locker Room, Coatroom, and Dressing Room Attendants	7
39-4011	Embalmers	7
39-4021	Funeral Attendants	6
39-4031	Morticians, Undertakers, and Funeral Arrangers	5
39-5011	Barbers	7
39-5012	Hairdressers, Hairstylists, and Cosmetologists	6
39-5091	Makeup Artists, Theatrical and Performance	5
39-5092	Manicurists and Pedicurists	7
39-5093	Shampooers	7
39-5094	Skincare Specialists	6
39-6011	Baggage Porters and Bellhops	6
39-7011	Tour Guides and Escorts	5
39-7012	Travel Guides	5
41-2011	Cashiers	7
41-2012	Gambling Change Persons and Booth Cashiers	7
41-2021	Counter and Rental Clerks	6
41-2022	Parts Salespersons	6

SOC Code	SOC Title	AER
41-2031	Retail Salespersons	5
41-3021	Insurance Sales Agents	5
41-3041	Travel Agents	5
41-4011	Sales Representatives, Wholesale and Manufacturing, Technical and Scientific Products	5
41-4012	Sales Representatives, Wholesale and Manufacturing, Except Technical and Scientific Products	5
41-9011	Demonstrators and Product Promoters	5
41-9012	Models	6
41-9041	Telemarketers	6
43-2011	Switchboard Operators, Including Answering Service	7
43-2021	Telephone Operators	7
43-3011	Bill and Account Collectors	5
43-3021	Billing and Posting Clerks	7
43-3031	Bookkeeping, Accounting, and Auditing Clerks	7
43-3041	Gambling Cage Workers	8
43-3051	Payroll and Timekeeping Clerks	7
43-3061	Procurement Clerks	5
43-3071	Tellers	7
43-4011	Brokerage Clerks	7
43-4021	Correspondence Clerks	6
43-4031	Court, Municipal, and License Clerks	6
43-4041	Credit Authorizers, Checkers, and Clerks	5
43-4051	Customer Service Representatives	6
43-4061	Eligibility Interviewers, Government Programs	6
43-4071	File Clerks	7
43-4081	Hotel, Motel, and Resort Desk Clerks	6
43-4111	Interviewers, Except Eligibility and Loan	5
43-4121	Library Assistants, Clerical	6
43-4131	Loan Interviewers and Clerks	5

SOC Code	SOC Title	AER
43-4141	New Accounts Clerks	6
43-4151	Order Clerks	5
43-4161	Human Resources Assistants, Except Payroll and Timekeeping	5
43-4171	Receptionists and Information Clerks	6
43-4181	Reservation and Transportation Ticket Agents and Travel Clerks	7
43-5011	Cargo and Freight Agents	6
43-5021	Couriers and Messengers	9
43-5031	Public Safety Telecommunicators	6
43-5032	Dispatchers, Except Police, Fire, and Ambulance	6
43-5041	Meter Readers, Utilities	9
43-5051	Postal Service Clerks	7
43-5052	Postal Service Mail Carriers	10
43-5053	Postal Service Mail Sorters, Processors, and Processing Machine Operators	9
43-5061	Production, Planning, and Expediting Clerks	6
43-5071	Shipping, Receiving, and Inventory Clerks	7
43-5111	Weighers, Measurers, Checkers, and Samplers, Recordkeeping	7
43-6011	Executive Secretaries and Executive Administrative Assistants	5
43-6012	Legal Secretaries and Administrative Assistants	5
43-6013	Medical Secretaries and Administrative Assistants	6
43-6014	Secretaries and Administrative Assistants, Except Legal, Medical, and Executive	6
43-9021	Data Entry Keyers	6
43-9022	Word Processors and Typists	7
43-9031	Desktop Publishers	5
43-9041	Insurance Claims and Policy Processing Clerks	7
43-9051	Mail Clerks and Mail Machine Operators, Except Postal Service	8
43-9061	Office Clerks, General	7
43-9071	Office Machine Operators, Except Computer	7
43-9081	Proofreaders and Copy Markers	8
45-1011	First-Line Supervisors of Farming, Fishing, and Forestry Workers	6
45-2011	Agricultural Inspectors	7
45-2021	Animal Breeders	6
45-2041	Graders and Sorters, Agricultural Products	8
45-2091	Agricultural Equipment Operators	6
45-2092	Farmworkers and Laborers, Crop, Nursery, and Greenhouse	7
45-2093	Farmworkers, Farm, Ranch, and Aquacultural Animals	6
45-3031	Fishing and Hunting Workers	7
45-4011	Forest and Conservation Workers	6
45-4021	Fallers	10
45-4022	Logging Equipment Operators	8
45-4023	Log Graders and Scalers	8
47-1011	First-Line Supervisors of Construction Trades and Extraction Workers	6
47-1011	Solar Energy Installation Managers	6
47-2011	Boilermakers	8
47-2021	Brickmasons and Blockmasons	7
47-2022	Stonemasons	6
47-2031	Carpenters	7
47-2041	Carpet Installers	7
47-2042	Floor Layers, Except Carpet, Wood, and Hard Tiles	6
47-2043	Floor Sanders and Finishers	7
47-2044	Tile and Stone Setters	8
47-2051	Cement Masons and Concrete Finishers	9
47-2053	Terrazzo Workers and Finishers	8
47-2061	Construction Laborers	7
47-2071	Paving, Surfacing, and Tamping Equipment Operators	8
47-2072	Pile Driver Operators	9
47-2073	Operating Engineers and Other Construction Equipment Operators	7
47-2081	Drywall and Ceiling Tile Installers	8
47-2082	Tapers	8
47-2111	Electricians	6
47-2121	Glaziers	7
47-2131	Insulation Workers, Floor, Ceiling, and Wall	8
47-2132	Insulation Workers, Mechanical	6
47-2141	Painters, Construction and Maintenance	7
47-2142	Paperhangers	7
47-2151	Pipelayers	9
47-2152	Plumbers, Pipefitters, and Steamfitters	7
47-2152	Solar Thermal Installers and Technicians	5
47-2161	Plasterers and Stucco Masons	7
47-2171	Reinforcing Iron and Rebar Workers	8
47-2181	Roofers	7
47-2211	Sheet Metal Workers	7
47-2221	Structural Iron and Steel Workers	8
47-2231	Solar Photovoltaic Installers	7
47-3011	Helpers--Brickmasons, Blockmasons, Stonemasons, and Tile and Marble Setters	8
47-3012	Helpers--Carpenters	8
47-3013	Helpers--Electricians	6
47-3014	Helpers--Painters, Paperhangers, Plasterers, and Stucco Masons	8
47-3015	Helpers--Pipelayers, Plumbers, Pipefitters, and Steamfitters	7
47-3016	Helpers--Roofers	7
47-4011	Construction and Building Inspectors	5
47-4011	Energy Auditors	5
47-4021	Elevator and Escalator Installers and Repairers	8
47-4031	Fence Erectors	7

SOC Code	SOC Title	AER
47-4041	Hazardous Materials Removal Workers	7
47-4051	Highway Maintenance Workers	7
47-4061	Rail-Track Laying and Maintenance Equipment Operators	7
47-4071	Septic Tank Servicers and Sewer Pipe Cleaners	8
47-4091	Segmental Pavers	6
47-4099	Weatherization Installers and Technicians	6
47-5011	Derrick Operators, Oil and Gas	9
47-5012	Rotary Drill Operators, Oil and Gas	8
47-5013	Service Unit Operators, Oil and Gas	7
47-5022	Excavating and Loading Machine and Dragline Operators, Surface Mining	8
47-5023	Earth Drillers, Except Oil and Gas	8
47-5032	Explosives Workers, Ordnance Handling Experts, and Blasters	7
47-5041	Continuous Mining Machine Operators	9
47-5043	Roof Bolters, Mining	10
47-5044	Loading and Moving Machine Operators, Underground Mining	9
47-5051	Rock Splitters, Quarry	9
47-5071	Roustabouts, Oil and Gas	7
47-5081	Helpers--Extraction Workers	7
49-1011	First-Line Supervisors of Mechanics, Installers, and Repairers	5
49-2011	Computer, Automated Teller, and Office Machine Repairers	7
49-2021	Radio, Cellular, and Tower Equipment Installers and Repairers	6
49-2022	Telecommunications Equipment Installers and Repairers, Except Line Installers	7
49-2091	Avionics Technicians	6
49-2092	Electric Motor, Power Tool, and Related Repairers	7
49-2093	Electrical and Electronics Installers and Repairers, Transportation Equipment	7
49-2094	Electrical and Electronics Repairers, Commercial and Industrial Equipment	6
49-2095	Electrical and Electronics Repairers, Powerhouse, Substation, and Relay	7
49-2096	Electronic Equipment Installers and Repairers, Motor Vehicles	6
49-2097	Audiovisual Equipment Installers and Repairers	5
49-2098	Security and Fire Alarm Systems Installers	6
49-3011	Aircraft Mechanics and Service Technicians	6
49-3021	Automotive Body and Related Repairers	7
49-3022	Automotive Glass Installers and Repairers	8
49-3023	Automotive Service Technicians and Mechanics	7
49-3031	Bus and Truck Mechanics and Diesel Engine Specialists	8
49-3041	Farm Equipment Mechanics and Service Technicians	8
49-3042	Mobile Heavy Equipment Mechanics, Except Engines	7
49-3043	Rail Car Repairers	7
49-3051	Motorboat Mechanics and Service Technicians	7
49-3052	Motorcycle Mechanics	8
49-3053	Outdoor Power Equipment and Other Small Engine Mechanics	7
49-3091	Bicycle Repairers	6
49-3092	Recreational Vehicle Service Technicians	7
49-3093	Tire Repairers and Changers	8
49-9011	Mechanical Door Repairers	7
49-9012	Control and Valve Installers and Repairers, Except Mechanical Door	7
49-9021	Heating, Air Conditioning, and Refrigeration Mechanics and Installers	6
49-9031	Home Appliance Repairers	7
49-9041	Industrial Machinery Mechanics	7
49-9043	Maintenance Workers, Machinery	7
49-9044	Millwrights	7
49-9045	Refractory Materials Repairers, Except Brickmasons	8
49-9051	Electrical Power-Line Installers and Repairers	8
49-9052	Telecommunications Line Installers and Repairers	7
49-9061	Camera and Photographic Equipment Repairers	7
49-9062	Medical Equipment Repairers	7
49-9063	Musical Instrument Repairers and Tuners	7
49-9064	Watch and Clock Repairers	7
49-9071	Maintenance and Repair Workers, General	7
49-9081	Wind Turbine Service Technicians	8
49-9091	Coin, Vending, and Amusement Machine Servicers and Repairers	9
49-9092	Commercial Divers	7
49-9094	Locksmiths and Safe Repairers	7
49-9095	Manufactured Building and Mobile Home Installers	6
49-9096	Riggers	8
49-9097	Signal and Track Switch Repairers	8
49-9098	Helpers--Installation, Maintenance, and Repair Workers	7
49-9099	Geothermal Technicians	7
51-1011	First-Line Supervisors of Production and Operating Workers	5
51-2011	Aircraft Structure, Surfaces, Rigging, and Systems Assemblers	7
51-2021	Coil Winders, Tapers, and Finishers	8
51-2022	Electrical and Electronic Equipment Assemblers	7
51-2023	Electromechanical Equipment Assemblers	8
51-2031	Engine and Other Machine Assemblers	8
51-2041	Structural Metal Fabricators and Fitters	7
51-2051	Fiberglass Laminators and Fabricators	8
51-2061	Timing Device Assemblers and Adjusters	6
51-2092	Team Assemblers	8
51-3011	Bakers	7
51-3021	Butchers and Meat Cutters	7
51-3022	Meat, Poultry, and Fish Cutters and Trimmers	8

SOC Code	SOC Title	AER
51-3023	Slaughterers and Meat Packers	9
51-3091	Food and Tobacco Roasting, Baking, and Drying Machine Operators and Tenders	7
51-3092	Food Batchmakers	9
51-3093	Food Cooking Machine Operators and Tenders	7
51-4021	Extruding and Drawing Machine Setters, Operators, and Tenders, Metal and Plastic	8
51-4022	Forging Machine Setters, Operators, and Tenders, Metal and Plastic	8
51-4023	Rolling Machine Setters, Operators, and Tenders, Metal and Plastic	8
51-4031	Cutting, Punching, and Press Machine Setters, Operators, and Tenders, Metal and Plastic	8
51-4032	Drilling and Boring Machine Tool Setters, Operators, and Tenders, Metal and Plastic	8
51-4033	Grinding, Lapping, Polishing, and Buffing Machine Tool Setters, Operators, and Tenders, Metal and Plastic	9
51-4034	Lathe and Turning Machine Tool Setters, Operators, and Tenders, Metal and Plastic	6
51-4035	Milling and Planing Machine Setters, Operators, and Tenders, Metal and Plastic	9
51-4041	Machinists	9
51-4051	Metal-Refining Furnace Operators and Tenders	8
51-4052	Pourers and Casters, Metal	7
51-4061	Model Makers, Metal and Plastic	8
51-4062	Patternmakers, Metal and Plastic	8
51-4071	Foundry Mold and Coremakers	9
51-4072	Molding, Coremaking, and Casting Machine Setters, Operators, and Tenders, Metal and Plastic	8
51-4081	Multiple Machine Tool Setters, Operators, and Tenders, Metal and Plastic	7
51-4111	Tool and Die Makers	7
51-4121	Welders, Cutters, Solderers, and Brazers	9
51-4122	Welding, Soldering, and Brazing Machine Setters, Operators, and Tenders	8
51-4191	Heat Treating Equipment Setters, Operators, and Tenders, Metal and Plastic	9
51-4192	Layout Workers, Metal and Plastic	7
51-4193	Plating Machine Setters, Operators, and Tenders, Metal and Plastic	8
51-4194	Tool Grinders, Filers, and Sharpeners	9
51-5111	Prepress Technicians and Workers	6
51-5112	Printing Press Operators	7
51-5113	Print Binding and Finishing Workers	8
51-6011	Laundry and Dry-Cleaning Workers	8
51-6021	Pressers, Textile, Garment, and Related Materials	9
51-6031	Sewing Machine Operators	9
51-6041	Shoe and Leather Workers and Repairers	7
51-6042	Shoe Machine Operators and Tenders	8
51-6051	Sewers, Hand	9
51-6052	Tailors, Dressmakers, and Custom Sewers	9
51-6061	Textile Bleaching and Dyeing Machine Operators and Tenders	9
51-6062	Textile Cutting Machine Setters, Operators, and Tenders	9
51-6063	Textile Knitting and Weaving Machine Setters, Operators, and Tenders	8
51-6064	Textile Winding, Twisting, and Drawing Out Machine Setters, Operators, and Tenders	9
51-6091	Extruding and Forming Machine Setters, Operators, and Tenders, Synthetic and Glass Fibers	8
51-6092	Fabric and Apparel Patternmakers	6
51-6093	Upholsterers	8
51-7011	Cabinetmakers and Bench Carpenters	8
51-7021	Furniture Finishers	7
51-7031	Model Makers, Wood	7
51-7032	Patternmakers, Wood	8
51-7041	Sawing Machine Setters, Operators, and Tenders, Wood	9
51-7042	Woodworking Machine Setters, Operators, and Tenders, Except Sawing	10
51-8011	Nuclear Power Reactor Operators	7
51-8012	Power Distributors and Dispatchers	6
51-8013	Power Plant Operators	7
51-8013	Biomass Plant Technicians	7
51-8013	Hydroelectric Plant Technicians	7
51-8021	Stationary Engineers and Boiler Operators	7
51-8031	Water and Wastewater Treatment Plant and System Operators	6
51-8091	Chemical Plant and System Operators	9
51-8092	Gas Plant Operators	7
51-8093	Petroleum Pump System Operators, Refinery Operators, and Gaugers	8
51-8099	Biofuels Processing Technicians	7
51-9011	Chemical Equipment Operators and Tenders	7
51-9012	Separating, Filtering, Clarifying, Precipitating, and Still Machine Setters, Operators, and Tenders	7
51-9021	Crushing, Grinding, and Polishing Machine Setters, Operators, and Tenders	8
51-9022	Grinding and Polishing Workers, Hand	7
51-9023	Mixing and Blending Machine Setters, Operators, and Tenders	9
51-9031	Cutters and Trimmers, Hand	8
51-9032	Cutting and Slicing Machine Setters, Operators, and Tenders	8
51-9041	Extruding, Forming, Pressing, and Compacting Machine Setters, Operators, and Tenders	8
51-9051	Furnace, Kiln, Oven, Drier, and Kettle Operators and Tenders	8
51-9061	Inspectors, Testers, Sorters, Samplers, and Weighers	7
51-9071	Jewelers and Precious Stone and Metal Workers	7
51-9071	Gem and Diamond Workers	9
51-9081	Dental Laboratory Technicians	6
51-9082	Medical Appliance Technicians	6
51-9083	Ophthalmic Laboratory Technicians	8
51-9111	Packaging and Filling Machine Operators and Tenders	8
51-9123	Painting, Coating, and Decorating Workers	7

SOC Code	SOC Title	AER
51-9124	Coating, Painting, and Spraying Machine Setters, Operators, and Tenders	9
51-9141	Semiconductor Processing Technicians	8
51-9151	Photographic Process Workers and Processing Machine Operators	6
51-9161	Computer Numerically Controlled Tool Operators	9
51-9162	Computer Numerically Controlled Tool Programmers	6
51-9191	Adhesive Bonding Machine Operators and Tenders	9
51-9192	Cleaning, Washing, and Metal Pickling Equipment Operators and Tenders	7
51-9193	Cooling and Freezing Equipment Operators and Tenders	7
51-9194	Etchers and Engravers	7
51-9195	Molders, Shapers, and Casters, Except Metal and Plastic	9
51-9195	Stone Cutters and Carvers, Manufacturing	7
51-9195	Glass Blowers, Molders, Benders, and Finishers	9
51-9195	Potters, Manufacturing	8
51-9196	Paper Goods Machine Setters, Operators, and Tenders	8
51-9197	Tire Builders	9
51-9198	Helpers--Production Workers	9
53-1041	Aircraft Cargo Handling Supervisors	6
53-1042	First-Line Supervisors of Helpers, Laborers, and Material Movers, Hand	5
53-1043	First-Line Supervisors of Material-Moving Machine and Vehicle Operators	5
53-2011	Airline Pilots, Copilots, and Flight Engineers	9

SOC Code	SOC Title	AER
53-2012	Commercial Pilots	6
53-2021	Air Traffic Controllers	6
53-2022	Airfield Operations Specialists	6
53-2031	Flight Attendants	7
53-3011	Ambulance Drivers and Attendants, Except Emergency Medical Technicians	7
53-3031	Driver/Sales Workers	9
53-3032	Heavy and Tractor-Trailer Truck Drivers	9
53-3033	Light Truck Drivers	8
53-3052	Bus Drivers, Transit and Intercity	9
53-4011	Locomotive Engineers	8
53-4013	Rail Yard Engineers, Dinkey Operators, and Hostlers	7
53-4022	Railroad Brake, Signal, and Switch Operators and Locomotive Firers	8
53-4031	Railroad Conductors and Yardmasters	8
53-4041	Subway and Streetcar Operators	10
53-5011	Sailors and Marine Oilers	8
53-5021	Captains, Mates, and Pilots of Water Vessels	7
53-5022	Motorboat Operators	8
53-5031	Ship Engineers	6
53-6011	Bridge and Lock Tenders	8
53-6021	Parking Attendants	8
53-6031	Automotive and Watercraft Service Attendants	8

SOC Code	SOC Title	AER
53-6041	Traffic Technicians	7
53-6051	Transportation Inspectors	6
53-6051	Aviation Inspectors	5
53-6051	Transportation Vehicle, Equipment and Systems Inspectors, Except Aviation	9
53-6061	Passenger Attendants	7
53-7011	Conveyor Operators and Tenders	8
53-7021	Crane and Tower Operators	8
53-7031	Dredge Operators	7
53-7041	Hoist and Winch Operators	9
53-7051	Industrial Truck and Tractor Operators	8
53-7061	Cleaners of Vehicles and Equipment	7
53-7062	Laborers and Freight, Stock, and Material Movers, Hand	8
53-7062	Recycling and Reclamation Workers	8
53-7063	Machine Feeders and Offbearers	9
53-7064	Packers and Packagers, Hand	7
53-7065	Stockers and Order Fillers	7
53-7071	Gas Compressor and Gas Pumping Station Operators	7
53-7072	Pump Operators, Except Wellhead Pumpers	7
53-7073	Wellhead Pumpers	6
53-7081	Refuse and Recyclable Material Collectors	10
53-7121	Tank Car, Truck, and Ship Loaders	8

[46]MIT, 2023. Workforce Effects of Automation and AI - Shaping the Future of Work Policy Memo.

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