

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



FOR MORE INFORMATION

Visit vtrans.virginia.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.

VTrans, Office of Intermodal Planning and Investment
1221 E. Broad Street, 2nd Floor, East Wing
Richmond, VA 23219
VTrans@oipi.virginia.gov

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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 |
| NO _x | 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 – NHTSA¹ 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 DMV² 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.
- Cohort² – A group of individuals having a statistical factor (such as age or class membership) in common in a demographic study
- Connected Vehicles – USDOT⁴ 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.
- Driver⁵ – 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
- Macrotrend⁶ – An emerging pattern of change likely to impact state government and require a response. More than one macrotrend can be associated with a megatrend.
- Megatrend⁵ – 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

- Resiliency⁷ – 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 Surge⁹ – Abnormal rise in seawater level during a storm, measured as the height of the water above the normal predicted astronomical tide.
- Vulnerability¹⁰ – 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 Scale¹¹ – 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

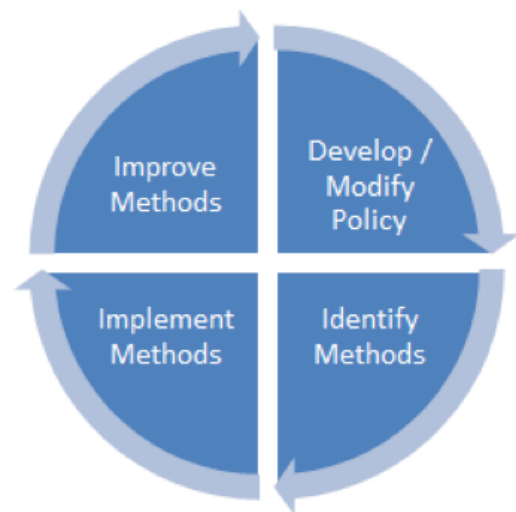
The execution of this Policy for the Development and Monitoring of the VTrans Long-term Risk & Opportunity Register relies on available research, availability of data at the desired spatial and temporal levels, and computations to ensure transparent, data-driven, and replicable methods. The following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

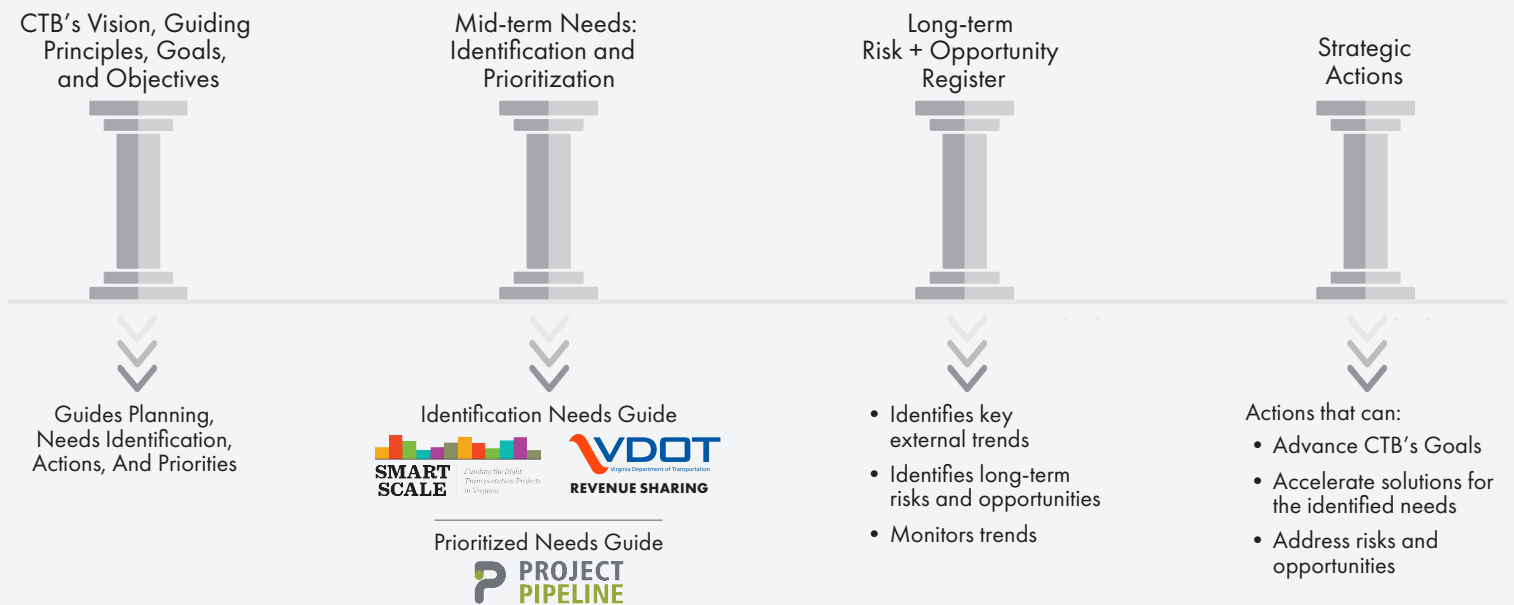
Figure 1-1: Opportunities for Continuous Improvement



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.

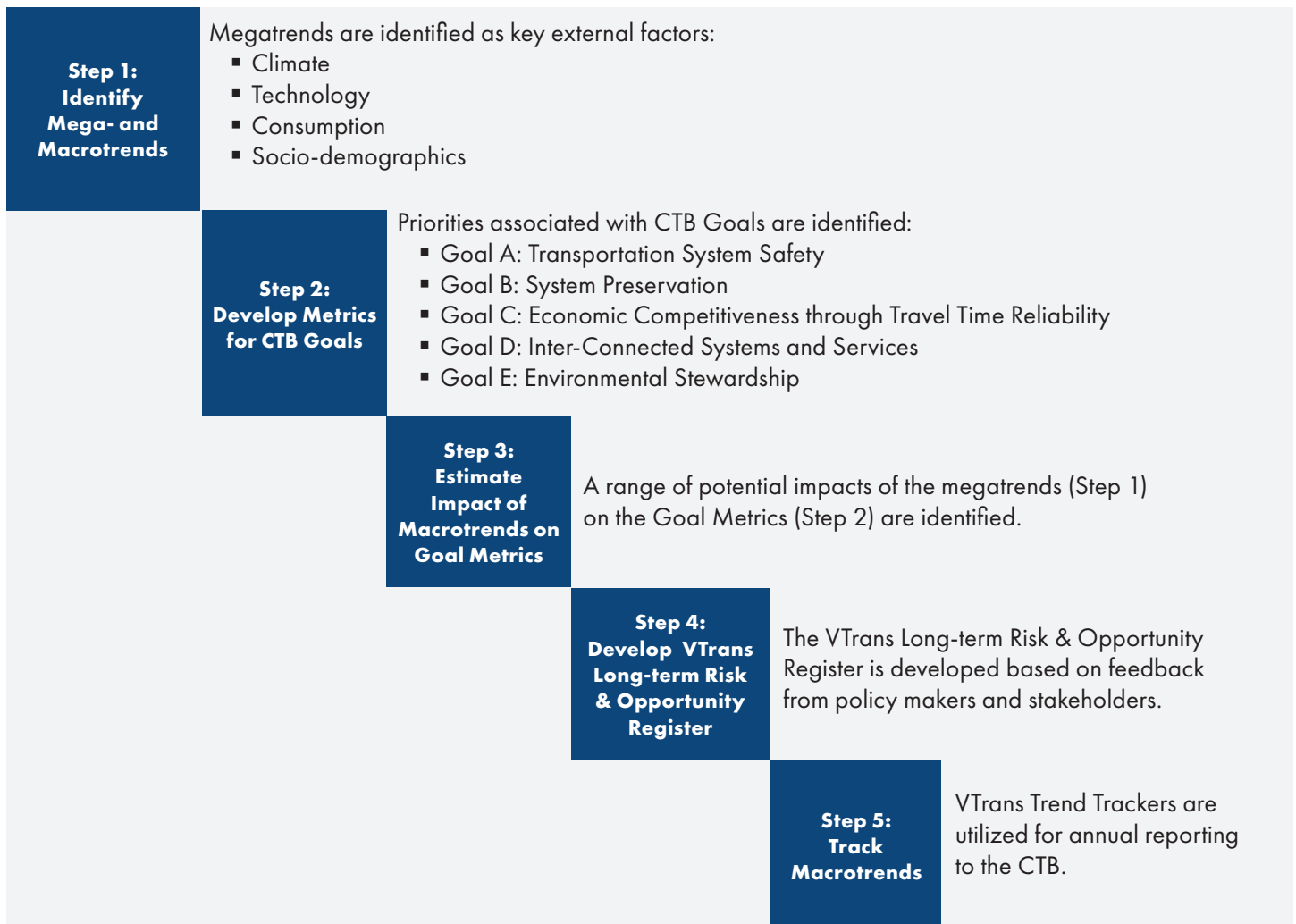
¹ [Office of Intermodal Planning and Investment of the Secretary of Transportation established pursuant to § 2.2-229](#)

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



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 lssu.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.

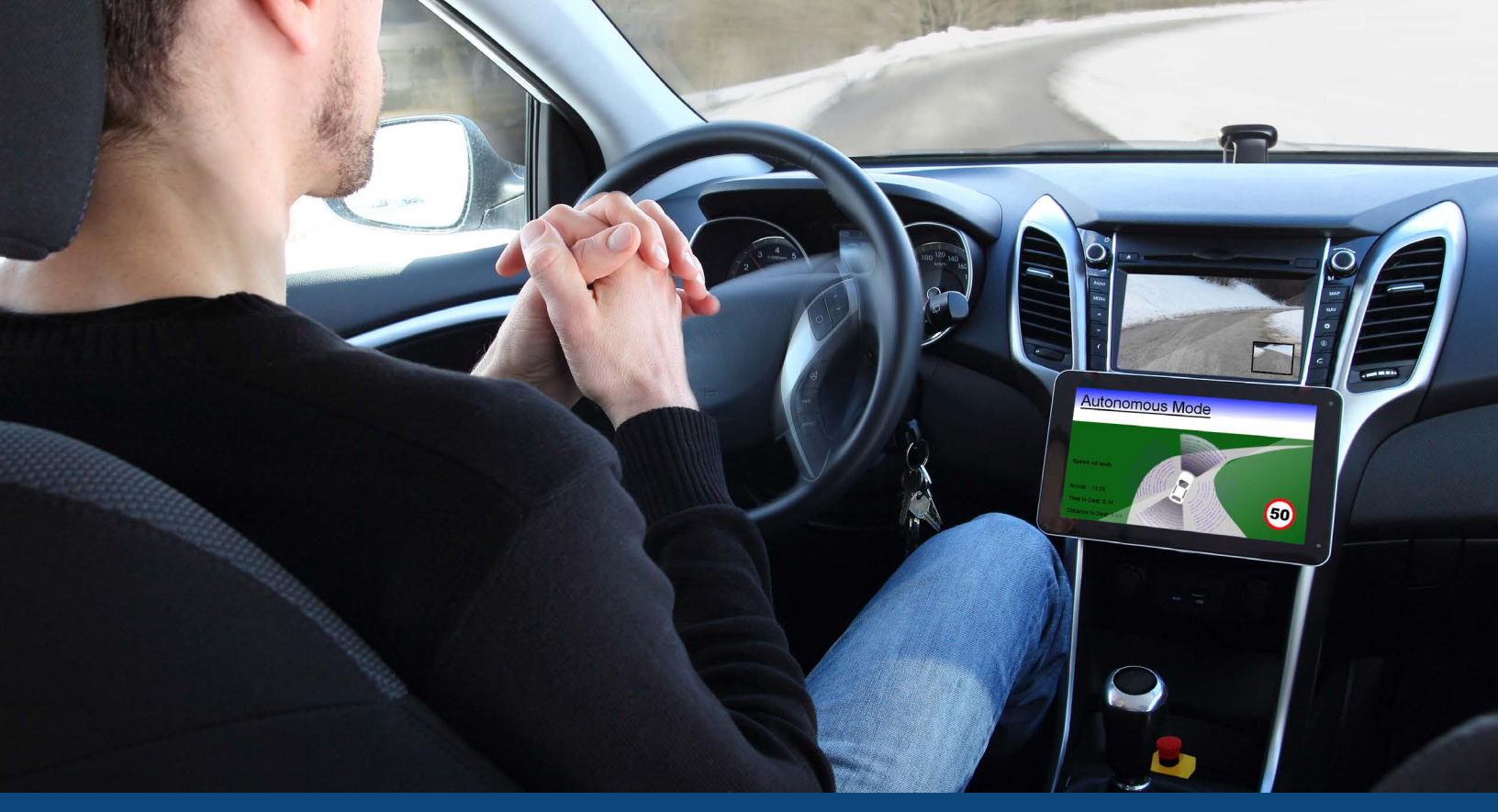
The sea level rise scenarios utilized Sewells Point tide gauge to determine Relative Sea Level Change (RSLC). With a baseline year 2000, these RSLC values were added to today’s mean high water (MHW) level to determine future MHW levels. These datasets were obtained from the Center for Coastal Resources 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.org⁶
- 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: FMCSA¹⁰

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:

$$\text{Stock_Tech}_i = \text{Stock_Tech}\% (t - 1) * (1 - S_i) + \text{NewSales_Tech}_i * S_i$$

Where,

Stock_Tech_i = Share of the total vehicle fleet equipped with the technology in year 't'

$\text{Stock_Tech}\% (t - 1)$ = Share of the fleet equipped with the technology in the previous year

NewSales_Tech_i = Share of newly sold vehicles equipped with the technology in year 't'

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

$(1 - S_i)$ = 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

$$Y_{L3/L4(t)} = \text{WillingnessToPay}_i * (1 - \text{PriceFactor}_i)$$

Where,

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

$\text{WillingnessToPay}_i$ = Consumer's Willingness-to-Pay in year 't'

PriceFactor_i = 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, Mihalil Goliias, and Evangelos Kaisar (2019).

¹⁰ Motor Carrier Census System. FMCSA. Accessed in March 2025

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

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

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)

$Y_{L3/L4(t)}$ = 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

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

Where,

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

$(1 - Y_{L3/L4(t)})$ = 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 technology¹
- Increased vehicle availability of EVs²
- Decreasing manufacturing costs³
- Growth in national charging infrastructure⁴

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: Replica⁷
- Shared Mobility Growth Rates: Uber and Lyft S-1 Filings^{8,9} and NACTO¹⁰
- TNC and Micromobility trip share (baseline): VTrans Biennial Transportation Survey 2022¹¹

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 micromobility¹² 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 percent¹⁵ 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 services¹⁶ 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.

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

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

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

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

¹⁶InteractVTrans | 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 convenience¹
- Consumer willingness to pay for delivery shipping services²
- Ease of making a return for an online purchase³
- Automation of warehousing⁴

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 Report⁷, Advance Monthly Sales for Retail and Food Services⁸, Annual Retail Trade Survey: 2018⁹, and County Business Patterns (CBP) Data¹⁰

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 Center¹¹
- U.S. Bureau of Labor Statistics (BLS), Quarterly Census of Employment & Wages (QCEW) Data¹² and County-Metropolitan Statistical Area (MSA)-CSA Crosswalk¹³
- U.S. Bureau of Economic Analysis (BEA), National Gross Domestic Product (GDP) by Industry¹⁴ and National Employment by Industry¹⁵
- 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.

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

Where:

- *Base E-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 Trade¹⁷
- *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 Trade¹⁸
- *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.

$$\text{Base E-com Sales } \%_i^{VA} = \sum_i (\text{Base E-com Sales } \%_i^{US} \times \text{Base Total Sales}_{ij}^{VA}) / \sum_i \text{Base Total Sales}_{ij}^{VA}$$

$$\text{Base E-com Sales}_{ij}^{VA} = \sum_i B(\text{Base E-com Sales } \%_i^{US} \times \text{Base Total Sales}_{ij}^{VA})$$

$$\text{Base E-com Emp}_{ij}^{VA} = \text{Base E-com Sales } \%_i^{VA} \times \text{Base Total Emp}_{ij}^{VA}$$

Where:

- *Base E-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* $\%_{ij}^{VA}$: Base year (2023) wholesale trade or B2B total (taxable) sales by NAICS industry *i* and Virginia geography *j*¹⁹
- *Base Total Emp* $\%_{ij}^{VA}$: 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.

- 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* = $0.061939 \times \ln(X-2001) + 0.137158$; $R^2 = 0.84$

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

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.

- 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.

Future Total Sales GF_i^{VA} = *Future Total Emp GF_i^{VA}* × *Future Productivity GF^{US}*

Where:

- Future Total Emp GF_i^{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 data²² and Employment by industry data.²³ The equation developed for productivity in future year X is as follows:
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.

- 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*.

Future Total Sales %_{i,j}^{VA} = *Future Total Sales GF_{sj}^{VA}* × *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.

$$\begin{aligned} \text{Future E-com Sales } \%_i^{US} &= \sum_i (\text{Future E-com Sales } \%_i^{US} \times \text{Future Total Sales}_{i,j}^{VA}) / \sum_i \text{Future Total Sales}_{i,j}^{VA} \\ \text{Future E-com Sales}_{i,j}^{VA} &= \sum_i (\text{Future E-com Sales } \%_i^{US} \times \text{Future Total Sales}_{i,j}^{VA}) \\ \text{Future E-com Emp}_{i,j}^{VA} &= \text{Future E-com Sales } \%_i^{VA} \times \text{Future Total Emp } GF_i^{VA} \times \text{Base E-com Emp}_{i,j}^{VA} \end{aligned}$$

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* $_{i,j}^{VA}$: 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* $_{i,j}^{VA}$: 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.

$$\text{Base E-com Sales } \%_i^{US} = \text{Base E-Com Sales}_{i,j}^{US} / \text{Base Total Sales}_{i,j}^{US}$$

Where:

- *Base E-Com Sales* $_{i,j}^{US}$: 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 Report²⁴
- *Base Total Sales* $_{i,j}^{US}$: 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 Services²⁵
- *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

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

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.

$$\text{Base E-com Sales \%}^{VA} = \sum_i (\text{Adj. Base E-com Sales \%}^{US}_i \times \text{Base Total Sales}_{ij}^{VA}) / \sum_i \text{Base Total Sales}_{ij}^{VA}$$

$$\text{Base E-com Sales}_{ij}^{VA} = \sum_i (\text{Adj. Base E-com Sales \%}^{US}_i \times \text{Base Total Sales}_{ij}^{VA})$$

$$\text{Base E''-com Emp}_i^{VA} = \text{Adj. Base E-com Sales \%}^{VA}_i \times \text{Base Total Emp}_i^{VA}$$

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_i^{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 Report³⁰, Advance Monthly Sales for Retail and Food Services³¹, and Annual Retail Trade Survey: 2018.³²

For retail trade or B2C sector:

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

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) Data³³**: 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 bankruptcies³⁴ 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 .

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

Where:

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

$$\text{Future E-com Sales } \%_i^{VA} = \frac{\sum_i (\text{Future E-com Sales } \%_i^{US} \times \text{Future Total Sales }_{i,j}^{VA})}{\sum_i \text{Future Total Sales }_{i,j}^{VA}}$$

$$\text{Future E-com Sales }_{i,j}^{VA} = \sum_i (\text{Future E-com Sales } \%_i^{US} \times \text{Future Total Sales }_{i,j}^{VA})$$

$$\text{Future E-com Emp }_i^{VA} = \text{Future E-com Sales } \%_i^{VA} \times \text{Future Total Emp } GF_i^{VA} \times \text{Base E-com Emp }_i^{VA}$$

Where:

- $\text{Future E-com Sales } \%_i^{US}$: Future year (2050) U.S. retail trade or B2C e-commerce market penetration rates for NAICS industry i estimated in calculation step #11
- $\text{Future Total Sales }_{i,j}^{VA}$: Future year (2050) retail trade or B2C total (taxable) sales by NAICS industry i and Virginia geography j estimated in calculation step #13
- $\text{Future Total Emp } GF_i^{VA}$: 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
- $\text{Base Total Emp }_i^{VA}$: 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 production¹
- 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 Crosswalk⁹
- Woods and Poole Complete Economic and Demographic Data Source (CEDDS)¹⁰
- Virginia Department of Taxation Annual Taxable Sales data via Weldon Cooper Center¹¹
- 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 Industry¹⁴
- O*NET® 29.3 Database, SOC and Work Activities, Work Context and Abilities¹⁵
- 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}

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

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

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

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

⁸U.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.

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

¹⁰Woods 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.

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

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

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

¹⁴U.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.

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

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

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

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

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

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

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

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

²⁴Babina, 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.

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

²⁶Omar 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).

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

²⁸Grandview 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.

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

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

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

³²3D 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.

$$\text{Base Emp}_{i,j}^{\text{VA}} = \text{Base Est}_{i,j}^{\text{VA}} \times (\text{Base Total Emp}_i^{\text{VA}} / \text{Base Total Est}_i^{\text{VA}})$$

Where:

- $\text{Base Est}_{i,j}^{\text{VA}}$: Base year (2023) establishments by NAICS industry i and Virginia geography j
 - $\text{Base Total Emp}_i^{\text{VA}}$: Base year (2023) total employment by NAICS industry i in Virginia
 - $\text{Base Total Est}_i^{\text{VA}}$: 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.

$$\text{Adj Base Emp}_{i,j}^{\text{VA}} = \text{Fratar Method applied to Base Emp}_{i,j}^{\text{VA}}$$

With $\text{Base Total Emp}_i^{\text{VA}}$ and $\text{Base Total Emp}_i^{\text{VA}}$ as control totals

Where:

$\text{Base Total Emp}_i^{\text{VA}}$: Base year (2023) total employment in manufacturing sector by Virginia geography j

$\text{Base Total Emp}_i^{\text{VA}}$: 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)

³³U.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 forecasts³⁴ 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 forecasts³⁵ 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.

³⁴Woods 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.

³⁵Woods 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

| | 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 |
| 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-Norhampton | 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) | | | 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 |
| 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) | | | 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 |
| 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 Mix³⁶ 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 **Low (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).

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

³⁷U.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 |

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

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

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

⁴¹Grandview 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.

⁴²Statzon, 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 added⁴³ 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*_{ij}^{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 **Low (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*_{ij}^{VA,Auto} as follows:

$$\text{Second Adj Future Emp}_{ij}^{VA,Low} = \text{Adj Future Emp}_{ij}^{VA,Low} + \text{Future Emp Loss}_{ij}^{VA,Auto}$$

f. Determine the likelihood of the automation related job loss to fall within a standard occupational classification (SOC) code. For this, apply LMI’s methodology⁴⁴ to O*NET 29.3 Database⁴⁵ 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.

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

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

⁴⁵O*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.

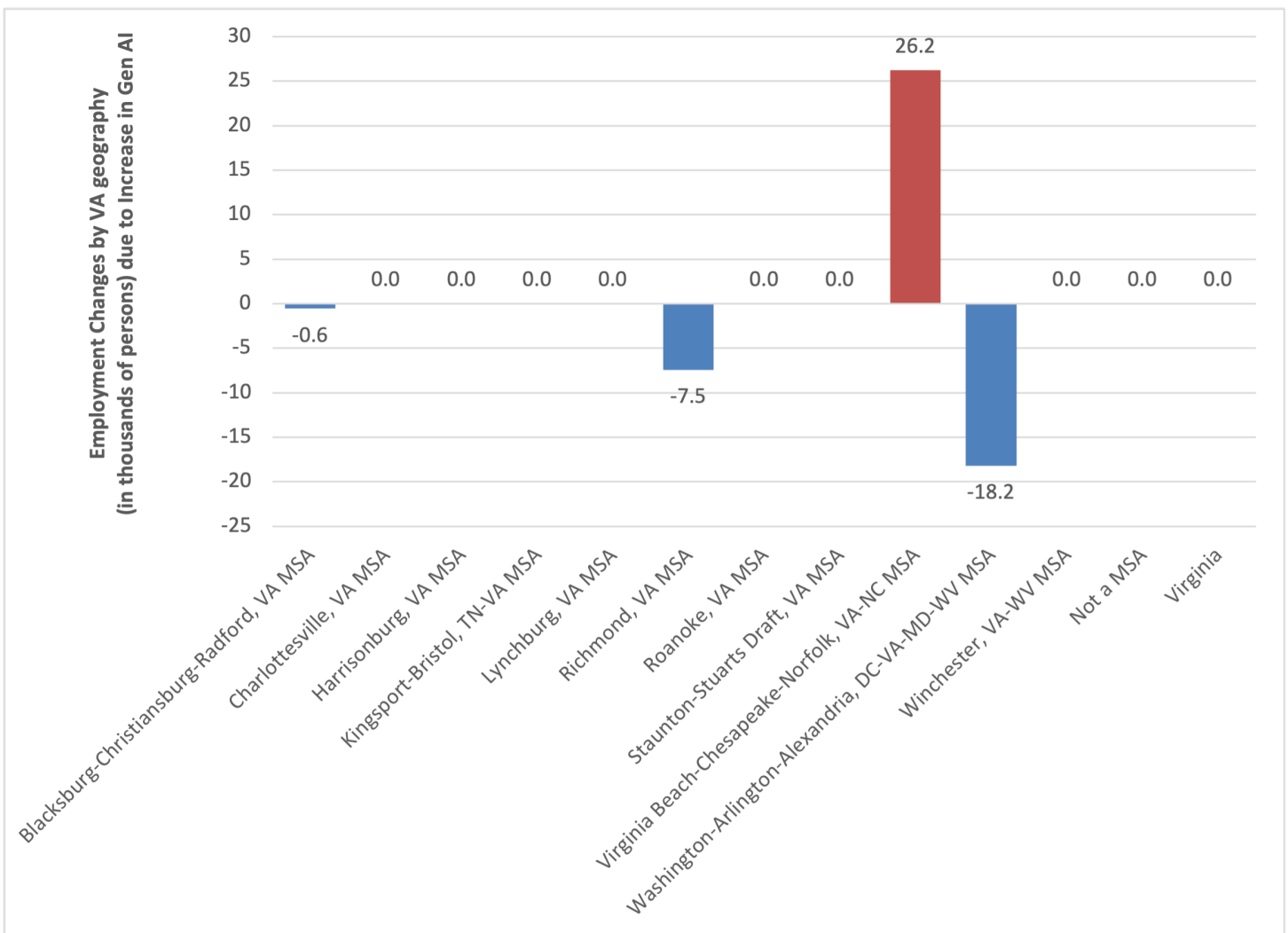
For example, in Washington-Arlington-Alexandria MSA, there are 145,714 jobs in high Gen AI and automation exposure occupations (the 44 occupations identified in Table 3.1.6-4). Of these, 12.5 percent, i.e., 18,214 jobs are expected to be displaced to another geography.

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 on 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, $Future\ Emp\ Geog\ Shift_{ij}^{VA, AI}$, 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 $Future\ Emp\ Geog\ Shift_{ij}^{VA, AI}$ as follows:
 Third Adj Future Emp_{ij}^{VA, Low} = Second Adj Future Emp_{ij}^{VA, Low} + Future Emp Geog Shift_{ij}^{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



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

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

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

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

⁵¹Federal 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 al⁵² 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:

$$\begin{aligned}
 & \text{Future AI Emp Shift}_{i,j}^{VA,AI} \\
 & = \text{Third Adj Future Emp}_{i,j}^{VA,Low} \times \text{Future AIJobsPerc}_i \\
 & - \text{Base Emp}_{i,j}^{VA,Low} \times \text{Base AIJobsPerc}_i
 \end{aligned}$$

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, $\text{Final Adj Future Emp}_{i,j}^{VA,Low} = \text{Third Adj Future Emp}_{i,j}^{VA,Low}$

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.

⁵²Babina, 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.

⁵³Babina, 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.

$$\text{Base Output}_i^{VA} = \text{Base GDP}_i^{VA} \times (\text{Base Output}_i^{US} / \text{Base GDP}_i^{US})$$

Where:

- Base GDP_i^{VA} : base year (2023) Real GDP (in chained 2017\$) for Virginia⁵⁴
- $\text{Base Output}_i^{US}$: 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.

$$\text{Adj. Base Sales}_{i,j}^{VA} = \text{Base Sales}_{i,j}^{VA} \times \text{Base Output}_i^{VA} / \sum_i \text{Base Sales}_{i,j}^{VA}$$

Where:

- $\text{Base Sales}_{i,j}^{VA}$: base year (2023) taxable sales by industry and Virginia geography⁵⁷

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.

$$\text{Base Sales}_{i,j}^{VA} = \text{Base Emp}_{i,j}^{VA} \times (\text{Base Output}_i^{VA} / \sum_i \text{Base Emp}_{i,j}^{VA})$$

Where:

- $\text{Base Emp}_{i,j}^{VA}$: 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.

$$\text{Base GM Sales}_i^{VA} = \sum_{i \in GM} \text{Base Sales}_{i,j}^{VA}$$

Where:

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

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

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

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

⁵⁷Virginia 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.

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

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 Data⁵⁸ 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 |

⁵⁸U.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.

⁵⁹U.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 industries⁶⁰ 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_{ij}^{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.

$$Future\ GM\ Sales_i^{VA} = \sum_{i \in GM} Future\ Sales_{i,j}^{VA}$$

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.

$$\text{Base 3DP Sales Share}^{VA} = \text{Base 3DP Sales}^{US} / \text{Base Mfg Sales}^{US}$$

Where:

- $\text{Base 3DP Sales}^{US}$: Base year (2023) U.S. sales for additive manufacturing or 3D printing based on Precedence Research on U.S. 3D printing market size⁶¹
- $\text{Base Mfg Sales}^{US}$: 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., $\text{Future 3DP Sales Share}^{VA}$ 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.

$$\begin{aligned} & \text{Base 3DP Emp}_{ij}^{VA} \\ &= \text{Base Mfg Emp}_i^{VA} \times \text{Base 3DP Sales Share}^{VA} \times \text{3DP Industry Group K Sales Share}_i^{US} \\ & \times (\text{Base Mfg Emp}_{ij}^{VA} / \sum_{i \in K} \text{Base Mfg Emp}_{ij}^{VA}) \end{aligned}$$

$$\begin{aligned} & \text{Base 3DP Sales}_{ij}^{VA} \\ &= \text{Base Mfg Sales}_i^{VA} \times \text{Base 3DP Sales Share}^{VA} \times \text{3DP Industry Group K Sales Share}_i^{US} \\ & \times (\text{Base Mfg Sales}_{ij}^{VA} / \sum_{i \in K} \text{Base Mfg Sales}_{ij}^{VA}) \end{aligned}$$

Where:

- $\text{Base Mfg Emp}_i^{VA}$: Base year (2023) manufacturing sector employment for Virginia geography j
- $\text{Base Mfg Sales}_i^{VA}$: Base year (2023) manufacturing sector sales for Virginia geography j
- $\text{3DP Industry Group K Sales Share}_i^{US}$: Additive manufacturing or 3D printing industry group K 's share of total additive manufacturing or 3D printing output
- $\text{Base Mfg Emp}_{ij}^{VA}$: Base year (2023) employment for manufacturing for industry i and Virginia geography j
- $\text{Base Mfg Sales}_{ij}^{VA}$: 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

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

⁶²U.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.

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

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

⁶⁵Omar 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.

$$\begin{aligned} & \text{Future 3DP Emp}_{i,j}^{VA} \\ &= \text{Future Mfg Emp}_i^{VA} \times \text{Future 3DP Sales Share}^{VA} \times \text{3DP Industry Group K Sales Share}_i^{US} \\ & \times (\text{Future Mfg Emp}_{i,j}^{VA} / \sum_{i \in K} \text{Future Mfg Emp}_{i,j}^{VA}) \end{aligned}$$

$$\begin{aligned} & \text{Future 3DP Sales}_{i,j}^{VA} \\ &= \text{Future Mfg Sales}_i^{VA} \times \text{Future 3DP Sales Share}^{VA} \times \text{3DP Industry Group K Sales Share}_i^{US} \\ & \times (\text{Future Mfg Sales}_{i,j}^{VA} / \sum_{i \in K} \text{Future Mfg Sales}_{i,j}^{VA}) \end{aligned}$$

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.

$$\text{Base 3DP Share}_i^{VA} = \text{Base 3DP Sales}_i^{VA} / \text{Base GM Sales}_i^{VA}$$

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.

$$\text{Future 3DP Share}_i^{VA} = \text{Future 3DP Sales}_i^{VA} / \text{Future GM Sales}_i^{VA}$$



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, 2023¹
- Woods & Poole's Employment Estimates for Virginia, 2023 and 2050²
- U.S. Bureau of Labor Statistics (BLS) STEM Occupations Share of All Occupations by 2-Digit NAICS Industry³, Ten-year Occupation Projections⁴
- 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 tools¹
- Availability, reliability, and speed of broadband services²
- Growth in high-end knowledge work tasks and product innovation with assistance from AI³

Data Sources:

- U.S. Bureau of Labor Statistics Employment Data for Virginia, 2023⁴
- Woods & Poole's Employment Estimates for Virginia, 2023 and 2050⁵
- U.S. Census, American Community Survey (ACS), Historical Work from Home Shares by Occupation Category⁶
- 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, 2023¹
- Woods & Poole’s Population Estimates for Virginia, 2023 and 2050²
- 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, 2023¹
- US Bureau of Labor Statistics Employment Data for Virginia, 2023²
- Woods & Poole’s Population, Employment and Household income Estimates for Virginia, 2023 and 2050³
- 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 3.1.10-1 through 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% |


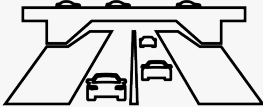

Table 3.1.10-2: Statewide Population and Mean Household Income Forecast (2050)

| 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 Objectives¹ (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 |
|---|---|---|
| <p>Goal A: Transportation System Safety Reduce fatalities and serious injuries to make the transportation network safer for the traveling public</p> | <p>A.1. Reduce the number and rate of motorized fatalities and serious injuries through implementation of the Strategic Highway Safety Plan.</p> <p>A.2. Reduce the number of non-motorized fatalities and serious injuries through implementation of the Strategic Highway Safety Plan.</p> <p>A.3. Reduce fatalities and serious injuries by implementing annual Safety Performance Targets in Public Transportation Agency Safety Plans.</p> | <p>Safety Index (Safety Index - Estimated Change in Number of Crashes with Fatalities + Serious Injuries Due to VTrans Macrotrends)</p>  |
| <p>Goal B: System Preservation Provide well-maintained and managed transportation infrastructure and services across the Commonwealth.</p> | <p>B.1. Obtain the following outcomes through the implementation of the recommendations from VDOT’s Maintenance and Operations Comprehensive Review.</p> <ul style="list-style-type: none"> ▪ 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. <p>B.2. Ensure transit state of good repair through the prioritization of investments and implementation of performance targets in Transit Asset Management plans.</p> <p>B.3. Ensure transit state of good repair through the prioritization of state capital investments in public transportation.</p> <p>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.</p> | <p>Roadways at Risk from Flooding</p>  |
| <p>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.</p> | <p>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.</p> <p>C.2. Improve freight throughput through the implementation of the Virginia Freight Plan and 2022 Statewide Rail Plan.</p> <p>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.</p> | <p>Vehicles Miles Traveled (VMT) Index (Estimated Change due to VTrans Macrotrends)</p>  |

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

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 | Included in the 2050 Business-as-usual Scenario | | | | |
| | 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 Kockelman¹
- Crash statistics for Virginia: VDOT²
- Number of fatal and serious injury crashes in Virginia: FHWA³
- Adoption of AV technologies between levels 1 and 4: Bansal and Kockelman⁴
- 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).
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 $q \in \{low, med, high\}$ with 2050 AV penetrations by level of automation:

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

Where:

- P_q^{L1-2} is the market penetration of Level 1-2 AVs
- P_q^{L3-4} 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.

$$\text{crashes compared to baseline} = \text{Safety Index} = \Delta VMT \times (1 - \text{potential crash rate reductions})$$

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

Where:

- 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).

$$\Delta \text{ Safety Index (2050)}$$

$$= K \text{ crashes} \times (K \text{ counts}) / (K \text{ counts} + A \text{ counts}) + A \text{ crashes} \times (A \text{ counts}) / (K \text{ counts} + A \text{ counts})$$

Where:

- $K \text{ crashes}$ is the estimated fatal crashes compared with baseline shown in the Table 3.3.3-2
- $A \text{ crashes}$ is the estimated serious injury crashes compared with baseline shown in Table 3.3.3-2
- $K \text{ counts}$ is the 7-year (2017-2024) average fatal injury crash count in Virginia.⁶
- $A \text{ counts}$ 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 2045²

| 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% | <i>If Bridge:</i> | | | |
| | | –Deck Rating | 2.5% | 2.5% | 2.5% |
| | | –Superstructure Rating | 2.5% | 2.5% | 2.5% |
| | | –Substructure Rating | 5.0% | 5.0% | 5.0% |
| | | <i>If Culvert:</i> | | | |
| | | –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.

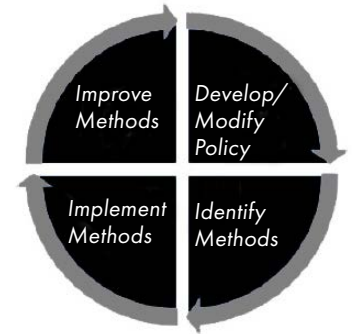
Table 3.3.2-5: Miles at Risk of Flooding by VDOT District and Planning District Commission

| | 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

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

Figure 3.3.2-1: Opportunities for Continuous Improvement



- **Data:** The execution relies on data from state and national sources. Each of these sources relies on various methods, techniques, and technologies to develop its datasets and, therefore, has its own limitations such as:
 - Lack of readily usable data: There are instances in which the current completeness and accuracy of datasets makes it unsuitable used to execute the methodology outlined in this technical memorandum. For example, more information on roadway horizontal and vertical geometry will significantly improve quality and accuracy of the vulnerability assessment results. Similarly, availability of alternative routes will help provide more relevant data to determine the Adaptive Capacity of a facility (more details in Section 2) and thereby improve accuracy of the VTrans Vulnerability Assessment. Therefore, application of transportation planning or engineering judgment is recommended prior to developing solutions.
 - Scope of the task: The availability of data largely governed the scope of the task. For example, more precise information on transit and rail assets can help make the VTrans Vulnerability Assessment more multimodal in nature.
- **Computations:** The sheer size and magnitude of the effort relies on complex computations to perform an analysis on more than one million roadway segments. The effort requires synthesis, format conversions, and computations, such as in the following examples, that could result in inadvertent errors.
 - Units: Different data sources have different units. Some datasets are available by directional segment, whereas other datasets are available at the area or sub-area level.
 - Levels of aggregations: Some datasets are more aggregated than others. For example, historical weather data are available as point data and were aggregated and assigned to roadway segments.
 - 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: Compostella²
- Vehicle Cost Elasticities: Dong et al.³ (2012)
- VDOT's Daily Vehicle Miles Traveled Data for Virginia⁴
- Commute modes: FHWA⁵
- Vehicle Travel Information System (VTRIS) Average Truck Gross Weight and Payload Data for Virginia⁶
- Vehicle Inventory Use Survey (VIUS), National Short- and Long-Haul Shares by Truck Weight Class⁷

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 Virginia⁸
- National retail federation's rate of return assumptions of auto-based in-store purchases and online purchases of retail trade⁹
- World Bank's home delivery routes of e-commerce shipments stops per day¹⁰
- National Household Travel Survey's (NHTS) average trip length for shopping trip purposes by MSA size and availability of heavy rail¹¹
- Average annual travel miles for Class 6 urban delivery truck¹²
- E-commerce mode split assumptions by MSA size¹³
- Percent of e-commerce deliveries asking for same-day delivery¹⁴ and small (less than 55 pounds) unmanned aerial vehicle (UAV) or drone use share assumption for the same-day delivery¹⁵
- Small UAV or drone haul distance assumption¹⁶

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 al¹⁷ (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, 2011, 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)*, Johansson & 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:

$$c_v = b \times a_v$$

$$MT_{2_3_4} (d) = AV \text{ Market Penetration} * \sum_v V c_v$$

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 .
- $AV \text{ Market Penetration}$ 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.

$$MT_4 = \text{new 2050 micromobility mileage} / \text{2050 private-auto VMT}$$

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.

¹⁹Taiebat, 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](#)

²⁰Cohen, 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.

²¹To 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).

$$\begin{aligned} & \text{Future E-com Sales Chg}_j^{VA} \\ &= \text{Future Output}_{i,GM}^{VA} \times \text{Future B2C Output Share}_i^{VA} \times \text{Future B2C E-com Sales \%}_j^{VA} \\ & - \text{Base Output}_{i,GM}^{VA} \times \text{Base B2C Output Share}_i^{VA} \times \text{Base B2C E-com Sales \%}_j^{VA} \end{aligned}$$

Where:

- $\text{Future Output}_{i,GM}^{VA}$: 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
 - $\text{Future B2C Output Share}_i^{VA}$: 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
 - $\text{Future B2C E-com Sales \%}_j^{VA}$: 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
 - $\text{Base Output}_{i,GM}^{VA}$: Base year (2023) goods movement dependent sectors total output in Virginia geography j based on Macrotrend #5
 - $\text{Base B2C Output Share}_i^{VA}$: 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
 - $\text{Base B2C E-com Sales \%}_j^{VA}$: 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.

$$\text{Future E-com Tons Chg}_j^{VA} = \text{Future E-com Sales Chg}_j^{VA} \times \text{ValPerTon}_{E-com}^{FAF}$$

Where:

- $\text{ValPerTon}_{E-com}^{FAF}$: 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:

$$\text{Future Dly Auto VMT Chg}_j^{VA,Pre} = \text{Future E-com Tons Chg}_j^{VA} \times (1 + \text{Return}\%_{\text{Shop at Store}}) \times \text{AvgTripLen}^{Auto} / \text{Payload}^{Auto} \times 300$$

b. Daily auto VMT added after the e-commerce change is calculated as follows:

$$\begin{aligned} & \text{Future Dly Auto VMT Chg}_j^{VA,Post} \\ &= (\text{Future E-com Tons Chg}_j^{VA} - \text{Drone E-com Tons Chg}_j^{VA}) \times (1 + \text{Return}\%_{\text{Online}}) \times \text{AvgTripLen}^{Auto} \times \text{E-com Mode}\%_{\text{Auto}} / \\ & \text{Payload}^{Auto} \times 300 \end{aligned}$$

²²U.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.

$$\begin{aligned}
& \text{Future Drone E-com Tons Chg}_i^{VA} \\
& = \text{Future Output}_{i,GM}^{VA} \times \text{Future B2C Output Share}_i^{VA} \times \text{Future B2C E-com Sales \%}_i^{VA} \\
& \times \text{Future Drone Delivery\%}_{E-com}^{US} \\
& - \text{Base Output}_{GM}^{VA} \times \text{Base B2C Output Share}_i^{VA} \times \text{Base B2C E-com Sales \%}_i^{VA} \\
& \times \text{Base Drone Delivery\%}_{E-com}^{US}
\end{aligned}$$

Where:

- $\text{Return\%}_{\text{Shop at Store}}$: Rate of return for shop at store, which is 16.7 percent²³
- $\text{Return\%}_{\text{Online}}$: Rate of return for shop at store, which is 20.2 percent²⁴
- $\text{AvgTripLen}^{\text{Auto}}$: 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 rail²⁵
- $\text{Payload}^{\text{Auto}}$: Assumed as 2,500 pounds per auto²⁶
- $\text{E-com Mode\%}^{\text{Auto}}$: 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
- $\text{Base Drone Delivery\%}_{E-com}^{US}$: Assumed as zero percent
- $\text{Future Drone Delivery\%}_{E-com}^{US}$: Assumed to reach 50 percent of the 25 percent²⁷ 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:

$$\text{Future Dly Net Auto VMT Chg}_i^{VA} = \text{Future Dly Auto VMT Chg}_i^{VA,Pre} - \text{Future Dly Auto VMT Chg}_i^{VA,Post}$$

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.

$$\begin{aligned}
& \text{Future Dly Dlvry Van VMT Chg}_i^{VA} \\
& = \text{Future E-com Tons Chg}_i^{VA} \times (1 + \text{Return\%}_{\text{Online}}) \times \text{AvgTripLen}^{\text{Van}} \times \text{E-com Mode\%}^{\text{Van}} / \text{Payload}^{\text{Van}} \times 300
\end{aligned}$$

$$\begin{aligned}
& \text{Future Dly Dlvry Trk VMT Chg}_i^{VA} \\
& = \text{Future E-com Tons Chg}_i^{VA} \times (1 + \text{Return\%}_{\text{Online}}) \times \text{AvgTripLen}^{\text{Trk}} \times \text{E-com Mode\%}^{\text{Trk}} / \text{Payload}^{\text{Trk}} \times 30
\end{aligned}$$

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

Where:

- $\text{Ann Mileage}^{\text{Trk Or Van}}$: Annual mileage for delivery truck or van, which is assumed as 30,000 miles²⁸
- $\# \text{ of Stops per Tour}^{\text{Trk Or Van}}$: 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 study²⁹
- $\text{AvgTripLen}^{\text{Van}} = \text{AvgTripLen}^{\text{Trk}}$: 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
- $\text{Payload}^{\text{Van}}$: Assumed as 4,000 pounds per delivery van³⁰
- $\text{Payload}^{\text{Trk}}$: Assumed as 8,000 pounds per delivery truck³¹

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

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

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

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

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

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

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

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

³¹Vehicle 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).

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

Where:

- *Future Mfg Output Share_i^{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 %_i^{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_i^{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 %_i^{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.

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

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.

³²U.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.

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

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

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

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

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 type³³
- **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 type³⁶
- **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 percent³⁷ 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 percent³⁸ 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 3.12³⁹ 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 percent⁴⁰ 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.

³³U.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.

³⁴U.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.

³⁵U.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.

³⁶U.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.

³⁷U.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.

³⁸U.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.

³⁹U.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.

⁴⁰U.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 ($HBW_auto_VMT \times 261$).
- $\% \Delta VMT^{total}_s$ is the net percent reduction relative to all-purpose annual VMT ($DVMT \times 365$).

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

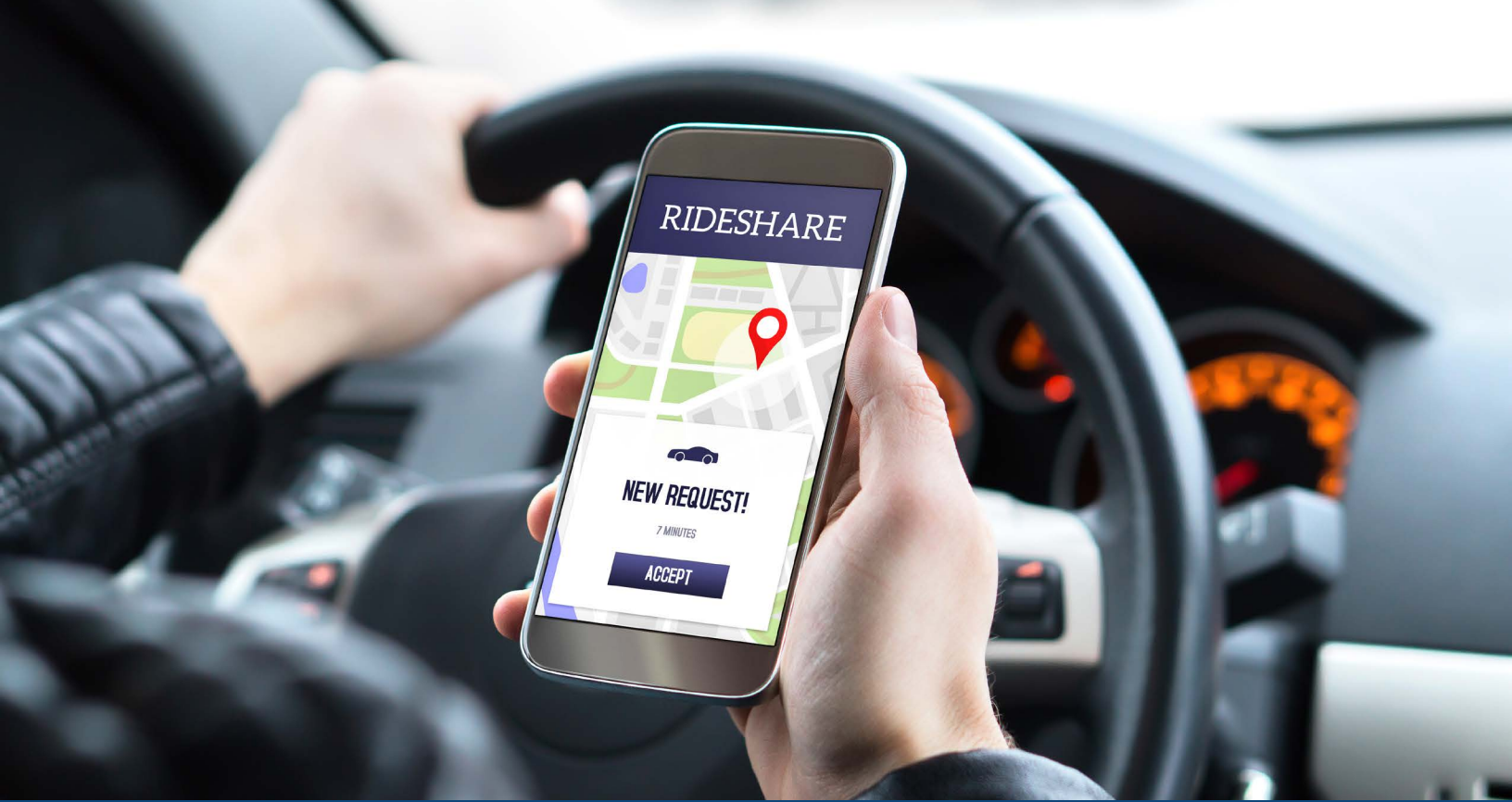
The results of calculation step # 22 are included in Table 3.3.1-7 and should be interpreted as follows:

- **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.

$$\text{shared mobility index (Ridesourcing)} = 1 + (\% \text{ VMT}_s \text{ switchable to TNC})$$

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.

$$\text{shared mobility index (Micromobility)} = 1 + (\% \text{ VMT}_s \text{ switchable to Micromobility})$$

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.

$$\text{shared mobility index} = 1 + (\% \text{ VMT}_s \text{ switchable to TNC} + \% \text{ VMT}_s \text{ switchable to Micromobility})$$

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 Administration²
- VMT in Virginia in 2022 by functional system: Federal Highway Administration³
- VMT in Virginia in 2022 by vehicle type: VDOT⁴
- 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: EPA⁵
- Emissions tonnage by vehicle weight class: EPA⁶
- Change in emissions due to electrification: Energy Innovations⁷
- 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) macro trends are expected to influence Tailpipe Emissions. The Macro trends' impact on tailpipe emissions is estimated under the relevant headers before being combined to derive a cumulative range of estimates for tailpipe emissions.

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

The combined impacts of Macro trend # 2: Adoption of Highly Autonomous Vehicles (AV), Macro trend # 3: Adoption of Electric Vehicles, Macro trend # 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 Macro trend # 4: Growth in Shared Mobility is calculated using the following steps:

2. Utilize calculation step output to obtain the reduction in VMT due to switching light vehicle trips to micromobility. The following equation is used for each scenario to account for the change in the light vehicle VMT due to shared mobility..

$$\Delta \text{light vehicles} = \Delta \text{VMT from Shared Mobility} \times 2022 \text{ DVMT all classes} / 2022 \text{ DVMT light}$$

Where:

- $\Delta \text{VMT from Shared Mobility}$ 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. Micromobility is assumed to be emissions-free.
- $2022 \text{ DVMT all classes}$ 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 Macro trend # 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 Macro trend # 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 Macro trend # 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 Macro trend # 8: Increase in Workplace Flexibility calculation in section 3.3.1.

Estimate the cumulative impacts of the previous Macrotrends:

- Combine the independent effects of each macrotrends' effect on that vehicle class's VMT using the following equation for the "low," "medium," and "high" scenarios for different vehicle weight classes.

$$\text{Combined effect} = \prod_{m \in M} (1 + \text{effect on VMT}_m)$$

Where:

- m is a Macrotrend out of all applicable macrotrends M .
- 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% |

- 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 |

- 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.

$$\text{Baseline emissions} = \sum_{v,v} \text{VMT}_v \times \text{tons per mile}_v \times \text{ICE emissions reduction}$$

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
- $\text{ICE emissions reduction}$ 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).

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

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)
- $\text{ICE emissions reduction}$ 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.

$$\text{Emissions (\%)} = 1 - \text{Expected emissions} / \text{Baseline Emissions}$$

Where:

- $\text{Baseline emissions}$ are emissions without the effects of any Macrotrends.
- $\text{Expected emissions}$ 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 risks¹ 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 |
|---|---|---|
|  |  | <ol style="list-style-type: none"> 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 |
| |  | <ol style="list-style-type: none"> 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 |
|---|--|
|  <p>1. Increase in Flooding Risk</p> | <ul style="list-style-type: none"> 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 |
|  <p>2. Adoption of Highly Autonomous Vehicles</p> | <ul style="list-style-type: none"> Market Penetration of Semi-Autonomous (Levels 1 and 2) Vehicles Attitude and Preferences for Adoption of Semi-Autonomous (Levels 1 and 2) Vehicles¹ Market Penetration of Highly Autonomous (Levels 3 and 4) Vehicles¹ Attitude and Preferences for Adoption of Highly Autonomous (Levels 3 and 4)¹ Vehicles |
|  <p>3. Adoption of Electric Vehicles</p> | <ul style="list-style-type: none"> Number of Electric Vehicles Market Penetration of Electric Vehicles Attitude and Preferences for Adoption of Electric Vehicles¹ Transportation Revenue by Revenue Source |
|  <p>4. Growth in Shared Mobility</p> | <ul style="list-style-type: none"> Access to Shared Mobility Services¹ Utilization of Shared Mobility Services by Type¹ |
|  <p>5. Growth in E-Commerce</p> | <ul style="list-style-type: none"> 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 |
|  <p>6. Greater Automation of Production and Services</p> | <ul style="list-style-type: none"> Number of short-range drone deliveries Number of long-range drone deliveries |
|  <p>7. Growth of Professional Services Industry</p> | <ul style="list-style-type: none"> Share of Professional Services Industry Jobs Number of STEM Jobs |
|  <p>8. Increase in Workplace Flexibility</p> | <ul style="list-style-type: none"> Number of Workers with Workplace Flexibility¹ Utilization of Workplace Flexibility¹ |
|  <p>9. Growth of the Age 65+ Cohort</p> | <ul style="list-style-type: none"> Number of Virginians with Age 65 or higher Share of Age 65+ Cohort |
|  <p>10. Population and Employment Shift</p> | <ul style="list-style-type: none"> 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

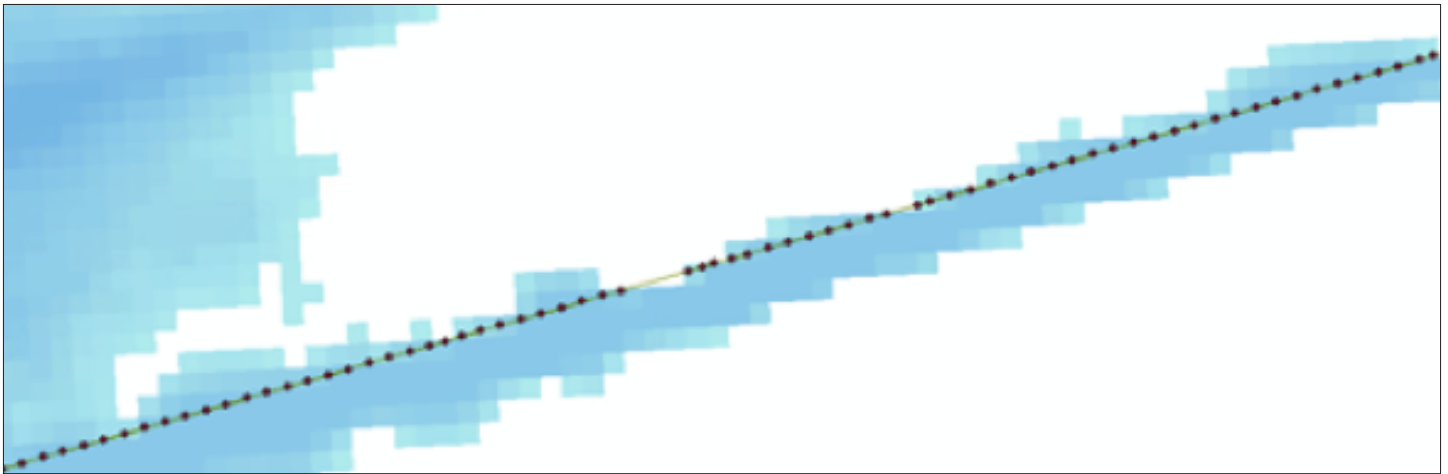
This appendix outlines the GIS steps performed to assess statewide exposure to sea level rise, storm surge, and inland/riverine flooding for the Commonwealth of Virginia. As noted in Section 1.5, this method does not account for roadway vertical geometry which might be different than ground surface elevations.

▪ 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 interval (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

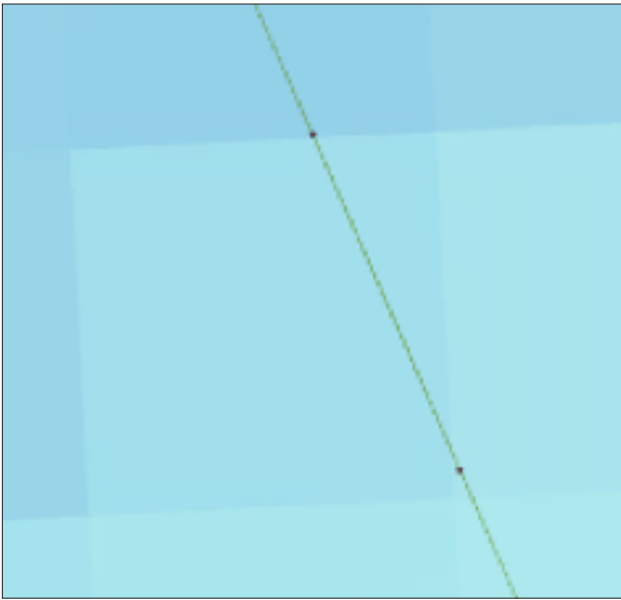


▪ Storm Surge

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

| SOC Code | SOC Title | AER |
|----------|--|-----|
| 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 |

| SOC Code | SOC Title | AER |
|----------|---|-----|
| 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 |

| SOC Code | SOC Title | AER |
|----------|---|-----|
| 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 |

| SOC Code | SOC Title | AER |
|----------|---|-----|
| 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 |

| SOC Code | SOC Title | AER |
|----------|---|-----|
| 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 |

| SOC Code | SOC Title | AER |
|----------|---|-----|
| 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 |

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

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