TRAVEL DEMAND MODELING POLICIES AND PROCEDURES

Version 3.00

Prepared for

Transportation and Mobility Planning Division
Virginia Department of Transportation

By

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CHAPTER 1. INTRODUCTION TO TRAVEL DEMAND MODELING IN VIRGINIA

This manual has been developed to provide guidance for public agencies in the Commonwealth of Virginia responsible for developing, validating, and applying travel demand models and their consultants. It is intended for readers who have a basic understanding of travel demand modeling concepts and procedures. In this manual, the terms "modeling" and "models" will refer to travel demand models.

This version of the manual, labeled Version 3.00, dated July 2020, is an update to the previous Version 2.00, dated June 2014.

Version 3 has a few major updates to Version 2.00, including the following:

- Regulation requirements affecting transportation modeling were updated (Section 1.2);
- New sections were added to address considerations of emerging transportation modes and trends in transportation modeling (Section 2.6), including transportation network companies (TNC), shared micromobility options, and connected and automated vehicles (CAVs);
- A section on uncertainty in travel demand models and ways to address modeling uncertainty was added (Section 2.7);
- Latest data sources and their applicability and limitations were discussed, including mobile location data, connected car and GPS tracking data, truck GPS data, and speed data (Section 4.2);
- Roles of survey data and their use cases were updated in the context of new data sources (Section 4.2);
- How new data sources can support model development was discussed, especially special generators, external travel, visitor travel, and truck and freight modeling;
- The Virginia Statewide Transportation Model (VSTM) was described and incorporated as part of truck and freight modeling (Chapter 8);
- Highway speed validation, including data sources, validation metrics, and reasonableness checks, is now included as part of the model validation process (Section 10.5); and
- Subarea modeling and analysis are described in detail, including planning application context, analytical methods, technical procedures, calibration and validation metrics, and model output refinements (Section 13.2).

1.1 What Is Travel Demand Modeling?

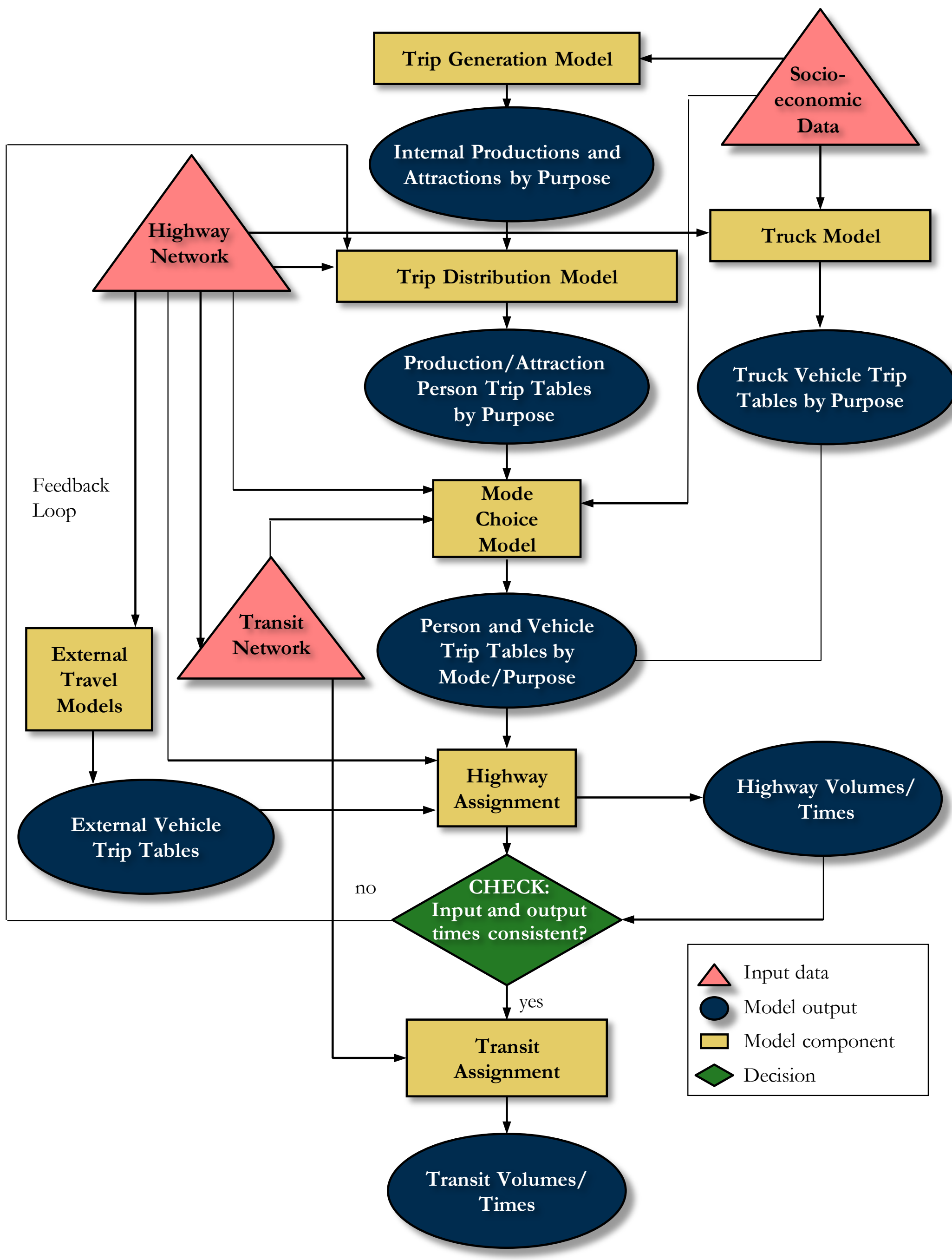
A travel demand model is an analytical tool used to support the transportation planning process. It can be used to develop traffic forecasts, test alternative transportation scenarios, and evaluate transportation systems or policies. Models are developed and applied using demographic, survey, and transportation system data, which are used to develop the transportation networks that are key components of the models. All of these data are used to develop the mathematical relationships necessary for modeling. A typical travel demand model in Virginia has between 10 and 30 input files and several output files.

Several different methodologies exist to perform modeling. The most common method used worldwide and in the United States is the conventional four-step approach. This is an aggregate sequential process with four basic steps:

- Trip Generation = How many trips will be made?
- Trip Distribution = Where will the trips go?
- Mode Choice = What modes of transportation will the trips use?
- Trip Assignment = What routes will the trips take?

Figure 1.1 illustrates a generic four-step modeling process, highlighting the typical major input data elements, model components, and model outputs. Demographic and other necessary model data is aggregated to transportation analysis zones (TAZs) for input to the model. TAZs generally follow census geography and are typically combinations of census blocks and/or census block groups. A discussion of how TAZs are defined appears in Section 4.1.

Figure 1.1 Four-Step Travel Demand Forecasting Process



1.2 Regulatory Requirements Affecting Transportation Modeling in Virginia

This section briefly summarizes regulatory requirements for transportation planning and travel models in urban areas. The requirements are up to date as of the time of the writing but are subject to change based on updated legislative and rulemaking actions.

A number of Federal and state regulations and requirements affect modeling in Virginia. These include:

1. Virginia Employment Commission Population Control Totals;
2. Federal Metropolitan Planning Regulations;
3. Federal Transportation Conformity Regulations; and
4. Federal Transit Administration Requirements.

1.2.1 Virginia Employment Commission Population Control Totals

The Code of Virginia stipulates that annual population estimates produced by the Weldon Cooper Center for Public Services at the University of Virginia shall be preferred over those estimates produced by the Census Bureau and used in any governmental formulae or decisions requiring population estimates. Currently, the Demographics & Workforce Group at the Weldon Cooper Center for Public Services produces annual official population estimates for Virginia and its counties and independent cities. In addition, it generates population projections that include total population and population by 18 age groups and by sex for each of the 133 localities in the Commonwealth. These estimates are generally released at the end of each January. Presented in Appendix B is Code of Virginia 15.2-4208 which states the duty of PDCs in preparing and maintaining population data. More detail related to population data preparation for model use can be found in Section 4.1.2 of this manual.

1.2.2 Federal Metropolitan Planning Regulations

Excerpts of relevant Federal law are provided in Appendix C. Federal law governing the metropolitan planning process is stated in Title 23 of the Code of Federal Regulations, Part 450, Subpart C, "Metropolitan Transportation Planning and Programming." (23 CFR 450.300-338). Travel demand models are one of the more commonly used tools to satisfy the metropolitan planning requirements. Among the key requirements of the regulations are:

- The metropolitan transportation planning process shall include the development of a transportation plan addressing at least a 20-year planning horizon.
- The Metropolitan Planning Organization (MPO) shall review and update the transportation plan at least every four years in air quality nonattainment and maintenance areas and at least every five years in attainment areas to confirm the transportation plan's validity and consistency with current and forecasted transportation and land use conditions and trends and to extend the forecast period to at least a 20-year planning horizon.

- The metropolitan transportation plan shall, at a minimum, include the current and projected transportation demand of persons and goods in the metropolitan planning area over the period of the transportation plan.

Appendix A to Part 450, "Linking the Transportation Planning and NEPA Processes," further emphasizes good practice when engaged in the transportation planning process, including recommending that "assumptions have a rational basis and are up-to-date" and that "data, analytical methods, and modeling techniques are reliable, defensible, reasonably current, and meet data quality requirements."

1.2.3 Federal Transportation Conformity Regulations

The Clean Air Act of 1990 established the first national air quality standards. These standards were amended in 1997 and renamed the national ambient air quality standards (NAAQS) to include some additional pollutants. The list of criteria pollutants addressed by the NAAQS is:

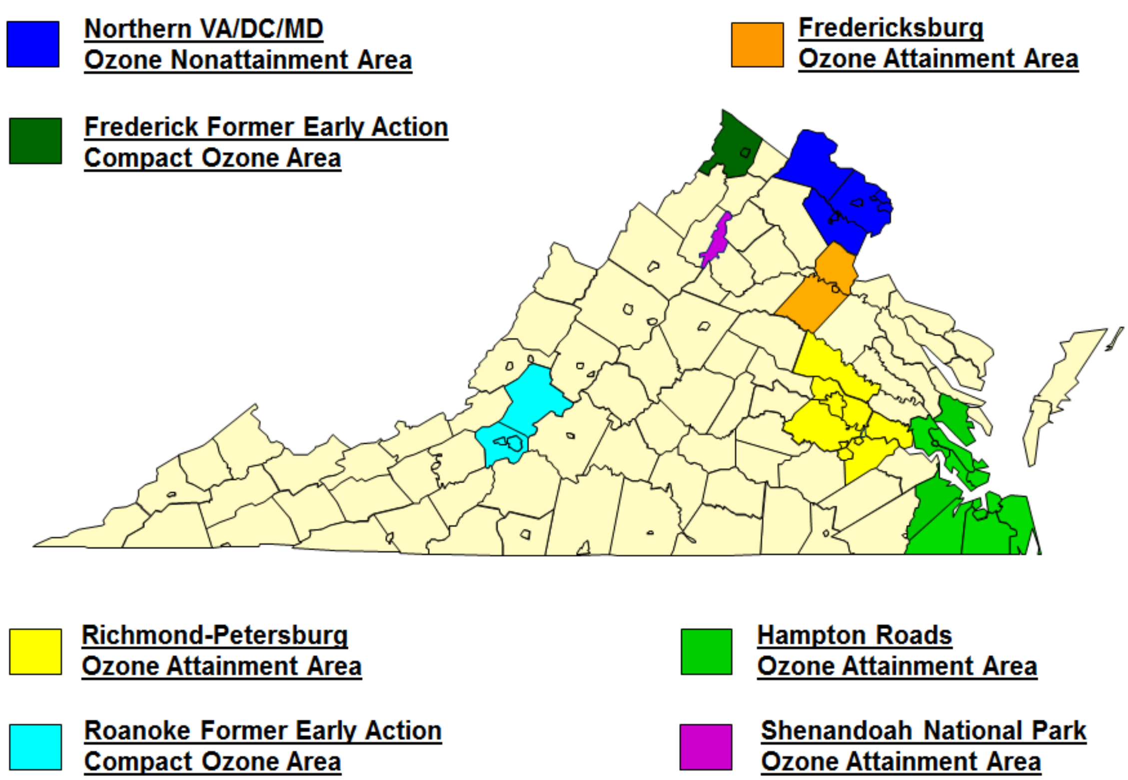
1. Ground-Level Ozone (O3);
2. Carbon Monoxide (CO);
3. Nitrogen Dioxide (NO2);
4. Lead (Pb);
5. Sulfur Dioxide (SO2);
6. Particulate Matter (PM2.5 and PM10)

Areas that have never been designated by EPA as nonattainment for one or more of the NAAQS are classified as attainment areas, while areas that do not meet one or more of the NAAQS may be designated by EPA as nonattainment areas for those pollutants. Areas that have failed to meet the NAAQS in the past but have since re-attained them may be re-designated as attainment areas, which are commonly referred to as maintenance areas. Figure 1.2 shows the air quality planning areas for the Commonwealth of Virginia. Table 1.1 shows that, with the exception of Northern Virginia, all MPO urban areas in Virginia are currently in attainment with all of the NAAQS as of January 1, 2020.

Nonattainment and maintenance areas are subject to transportation conformity requirements. Transportation conformity is required by the Clean Air Act section 176(c) (42 U.S.C. 7506(c)) to ensure that federal funding and approval are given to highway and transit projects that are consistent with ("conform to") the air quality goals established by a state air quality implementation plan (SIP). Conformity, to the purpose of the state implementation plan (SIP), means that transportation activities will not cause new air quality violations, worsen existing violations, or delay timely attainment of the national ambient air quality standards.

In areas subject to transportation conformity requirements, and in order for transportation projects to receive Federal assistance under Title 23, the MPO must perform an air quality conformity determination to assess the impact of the planned roadway improvements on regional air quality. This is typically accomplished with the assistance of the VDOT Environmental Division, Air Quality Section. The conformity analysis is performed on the MPO's adopted Long-Range Transportation Plan (LRTP) and Transportation Improvement Program (TIP) using a combination of Travel Demand Management (TDM) and Air Quality (AQ) emissions modeling processes. The vehicle emissions estimated for these analyses must conform to the emissions budgets established by the applicable SIP. Regional air quality analysis must meet additional modeling requirements for metropolitan planning areas with populations greater than 200,000 and that are in nonattainment for serious, severe, or extreme ozone or serious carbon monoxide. These requirements are stated in 40 CFR §93.122(b), which is excerpted in Appendix C. The population requirement applies to the size of the entire area and not only the portion in Virginia. For that reason Table 1.1 shows the entire multistate population, not only the portion in Virginia.

Figure 1.2 Air Quality Planning Areas for the Commonwealth of Virginia



Per a recent court decision (South Coast Air Quality Management District vs. EPA, February 2018), all areas in the country that were in nonattainment or maintenance for the 1997 ozone NAAQS before its revocation by EPA in 2015 were again made subject to transportation conformity requirements for that standard. This decision in part affects "orphan areas", which in Virginia includes the Fredericksburg, Richmond/Tri-Cities, and Hampton Roads regions. Beginning February 16, 2019,, transportation conformity requirements again apply to the applicable MPOs in these regions. In these orphan areas, transportation conformity for transportation plans and TIPs for the 1997 ozone NAAQS can be demonstrated without a regional emissions analysis, but the remaining criteria need to be met, including use of the latest planning assumptions, consultation requirements, timely implementation of any approved SIP transportation control measures (TCMs), and fiscal constraint. Please coordinate with the VDOT Environmental Division, Air Quality Section, to meet transportation conformity requirements for the development of any new or amended TIPs and LRTPs that contain regionally significant projects in these areas.

Table 1.1 NAAQS Status of MPOs in Virginia

Urban Area	MPO	States	2010 Census Population	Attainment Status	NAAQS Problem
Washington, D.C. region (includes Northern Virginia)	National Capital Region Transportation Planning Board (TPB)	D.C., Maryland, Virginia	5,068,737	Marginal Non-attainment	Marginal: 2015 Ozone
Hampton Roads	Hampton Roads Transportation Planning Organization	Virginia	1,622,372	Attainment	
Richmond	Richmond Area MPO	Virginia	928,765	Attainment	
Fredericksburg	Fredericksburg Area MPO	Virginia	275,644	Attainment	
Roanoke	Roanoke Valley MPO	Virginia	231,337	Attainment	
Lynchburg	Central Virginia MPO	Virginia	153,316	Attainment	
Petersburg	Tri Cities Area MPO	Virginia	154,407	Attainment	
Charlottesville	Charlottesville-Albemarle MPO	Virginia	122,809	Attainment	
Staunton-Augusta-Waynesboro	Staunton-Augusta-Waynesboro MPO (SAWMPO)	Virginia	78,794	Attainment	
Christiansburg	New River Valley MPO	Virginia	100,038	Attainment	
Winchester	Winchester-Frederick County MPO (WinFredMPO)	Virginia	78,616	Attainment	
Harrisonburg	Harrisonburg-Rockingham MPO (HRMPO)	Virginia	74,372	Attainment	
Martinsville	Danville MPO	Virginia	65,689	Attainment	
Kingsport	Kingsport MPO	Tennessee, Virginia	127,775	Attainment	
Bristol	Bristol MPO	Tennessee, Virginia	83,167	Attainment	

Note: [a] See Appendix D for EPA designations for the Washington region for Ozone Season Volatile Organic Compounds (VOC), Nitrogen Oxides (NO_x), Fine Particles ($PM_{2.5}$), and Wintertime Carbon Monoxide (CO).

1.2.4 Federal Transit Administration Planning Requirements

Model applications intended to support application through the Federal Transit Administration (FTA) New Starts Program can lead to additional requirements beyond those specified for metropolitan planning and conformity. FTA has provided guidance on what it considers as the five key aspects of travel forecasts for project evaluation under the New Starts, Small Starts, and (by extension) Core Capacity, programs [1]:

1. The properties of the forecasting methods;
2. The adequacy of current ridership data to support useful tests of the methods;
3. The successful testing of the methods to demonstrate their grasp of current ridership;
4. The reasonableness of inputs (demographics, service changes) used in the forecasts; and
5. The plausibility of the forecasts for the proposed project.

FTA also lists three approaches to prepare ridership forecasts:

- Region-wide travel models;
- Incremental data-driven methods; and
- Simplified Trips-on-Project Software (STOPS).

The "Major Capital Investment Projects" rules established in April 2013 revised the measures for FTA to use in evaluating and rating proposed major transit projects. Mobility benefits are measured as the predicted number of trips that would use the project, with a weight of 2.0 applied to project trips that would be made by transit dependents. The predicted change in automobile vehicle-miles of travel (VMT) is a component of the measure of environmental benefits of proposed projects. To implement the rules, FTA has developed a simplified method to quantify the revised measures, which include the predicted number of trips that would use the project, project trips that would be made by transit dependents, and the predicted change in automobile VMT. STOPS was developed to "predict detailed transit travel patterns for the No-build and Build scenarios, quantify the trips-on-project measure for all travelers and for transit dependents, and compute the change in automobile VMT based on the change in overall transit ridership between the two scenarios." [2]

STOPS characteristics include:

- STOPS can be used for ridership forecasts for fixed guideways, but it cannot be used for evaluation of local buses and for highway studies or air quality analysis;

- STOPS estimates transit demand that is not constrained by transit system capacity, and thus cannot be used to study transit system capacity relief projects;
- STOPS considers routine weekday trips by residents, including home-based work, home-based non-work, and non-home-based trip purposes, but it does not consider special travel markets such as college students, air passengers or visitor travel;
- STOPS uses worker-flows from the Census Transportation Planning Products (CTPP) to represent work trip patterns and uses the predicted locations of home-based transit attractions to estimate non-home-based trips;
- STOPS predicts future transit demand by using population and employment forecasts to adjust the 2000 CTPP travel patterns, which does not incorporate the effects of accessibility changes on travel patterns due to changes in the transportation system supply; and
- STOPS uses the zone-to-zone roadway travel times and distances from the regional travel model to adjust the zone-to-zone bus runtime, and it does not incorporate bus runtime changes due to revised bus routings, street improvements, and other localized changes.

STOPS has a simplified conventional trip-based model structure, with the following components:

- Travel patterns and trip tables estimated from the CTPP worker flow tabulations;
- A mode-choice model to predict zone-to-zone transit travel based on zone-to-zone travel characteristics of the transit and roadway networks; and
- A transit assignment to assign transit trips to fixed guideways in the transit network.

Motorized travel is stratified into home-based work, home-based non-work, and non-home-based trip purposes. The worker-flow tabulations from the CTPP are factored to represent home-based work-trip patterns and home-based non-work-trip patterns. The non-home-based travel market is approximated based on the use of an approach derived from the National Cooperative Highway Research Program Report 716, Travel Demand Forecasting: Parameters and Techniques. These travel patterns and trip tables are scaled based on population and employment forecasts for a future horizon year.

STOPS is primarily used in the following two ways:

- As a useful alternative when locally maintained methods – either the regional model or an incremental model – are unavailable or not sufficiently tailored to the task; and
- In a quality-control role – providing a second ridership forecast for comparison to a forecast prepared with locally maintained methods.

The timelines for submittal of travel forecasting information to the FTA differ by the approach taken, as shown in Table 1.2.

Table 1.2 Timelines for Submittal of Travel Forecasting Information

Information for FTA Review	Region-wide Model	Incremental Model	STOPS
	Months in advance of anticipated ratings request		
Documentation of the model methodology	4	3	N/A
Documentation of model testing	4	3	N/A
Documentation of project-specific inputs	3	3	2
Draft-final forecasts for the project	2	2	1

Source: FTA, "Travel Forecasts", https://www.transit.dot.gov/funding/grant-programs/capital-investments/travel-forecasts, accessed June 20, 2020.

When deciding which one of the three approaches to take, agencies that sponsor a fixed guideway transit project with the intent to seek the New Starts funding will need to consider several factors, including the resources available, project schedule, the nature of a project (e.g., a new mode or an extension of the existing guideway), the availability and rigor of a regional travel demand model, and the FTA requirements and timeline for travel forecasting information. If STOPS is used to prepare the ridership forecasts, FTA considers only the last two of the five aspects listed above. If region-wide travel models or incremental data-driven methods are used, FTA will consider all five aspects listed above when reviewing the forecasts. Clearly, the FTA scrutiny is the highest for taking the regional travel demand model approach and the lowest for using STOPS. When using a region-wide model, the original calibration and validation as part of the model development is typically not sufficient to satisfy the FTA requirements, and further model testing will need to be done, especially in the study corridor and with more detailed transit market data. An incremental modeling approach tends to be used in a situation where an extension of an existing guideway is pursued and sufficient transit market data can be used as the basis for pivoting off to support the evaluation of the extension. STOPS offers a streamlined procedure for conducting ridership forecasting and tends to have less demand for resources and time needed. However, STOPS has its own limitations, especially posing challenges for those study areas that are expected to have travel market patterns change considerably from the existing ones, e.g., with recent and anticipated rapid growth and some planned special generators for transit markets that do not exist. A region-wide model provides a great flexibility but requires more work and interactions with the FTA to pass muster for the New Starts ridership forecasting. In general, regardless of the application path selected, it would be wise to consult with FTA early on to confirm the latest specific requirements before embarking on the forecasting effort.

The discussion below is based on Appendix A, Section A.3 of National Cooperative Highway Research Program (NCHRP) *Report 716, Travel Demand Forecasting: Parameters and Techniques* [3], which draws on information from an FTA workshop [4]. Readers are referred to *NCHRP Report 716* for more detailed information.

FTA provides guidance on the following key aspects of travel forecasting for New Starts:

- Properties of travel models;
- Rider surveys; and
- Calibration and validation.

FTA's requirements for the properties of travel models are fairly broad. FTA supports a localized approach to travel modeling and forecasting, recognizing that there are no standard or "correct" methods that are universally applicable to all regions. Models need to reflect the fact that each metropolitan area has unique conditions and must be responsive to local decision making.

FTA's requirements are geared toward reasonably accounting for current patterns and predicting reasonable future ridership for the proposed New Starts projects. FTA does not provide rigid targets for parameters in travel models. Rather, FTA recommends methods that can be used to ensure that models reflect current travel behavior and predict reasonable future patterns.

FTA's expectations from travel models and the New Starts process can be summarized as follows:

- Coherent narrative of the model parameters, inputs, and outputs;
- Regular and early communication regarding model parameters and forecasts to ensure that the agency/sponsor is proceeding in the proper direction;
- Reasonable model forecasts in light of the expected land use growth, service characteristics, and other project-related attributes; and
- Proper documentation and uncertainty analysis.

Because models are used to forecast transit ridership, it is essential that they explain the current transit conditions and capture the tradeoffs between travel times and costs. These favorable properties are dependent on model validation procedures (see Chapter 3). In addition to capturing current conditions, models will need to fulfill their ultimate objective of yielding reasonable forecasts. Specifically, FTA requires reasonable "deltas" (changes in ridership between a base year and forecast year) for ridership that are consistent with the underlying socioeconomic growth as well as level-of-service improvements.

Rider surveys (see Section 4.2.1) are an important source of current transit information and are crucial to calibrating models that reflect the current conditions accurately. Where possible, FTA recommends surveys before and after project opening to get a time-varying picture of ridership patterns and also to evaluate the model predictions. The success of rider surveys in capturing the current transit travel patterns depends on the design of the surveys in terms of the sampling plan, the questionnaire, and the data items included in the questionnaire. In addition to the rider surveys, FTA recommends the use of other ridership data, where available, to inform the modeling process. These data could include on-off counts and park-and-ride utilization counts.

FTA emphasizes that forecasts should be based on models that are tested rigorously against current transit ridership patterns. The implications of a careful calibration and validation methodology are threefold: first, it necessitates better current data; second, it calls for a better focus on transit markets; and third, it requires better tests and standards.

FTA recommends that project sponsors take advantage of the funding and guidance opportunities available from the FTA to collect good quality "before" and "after" survey data. The issue of better focus on transit markets can be achieved through an evaluation of model performance by each trip purpose, socioeconomic group, production-attraction area types, and transit access modes. The FTA deems the matching of overall target totals as an insufficient measure of model calibration. The standards for model calibration must rely as much on behavioral significance as they do on statistical significance. The FTA defines validation as a valid description of travel behavior as well as plausible forecasts of "deltas" for the future year. The FTA recommends careful documentation of key transit markets, current transit modes, and calibration forecasts to help evaluate the overall effectiveness of the model.

The FTA has provided guidance on specific properties of travel models to ensure proper calibration and validation. The FTA has found that many travel models have one or more of the following problems:

- Unusual coefficients in mode choice models;
- Bizarre alternative-specific constants;
- Path/mode choice inconsistencies[1];
- Inaccurate bus running times; and
- Unstable highway-assignment results.

Since naïve calibration leads to bad alternative-specific constants and has the cascading effect of producing errors in trips and benefits, the FTA suggests that modelers ask themselves if patterns across market segments are explainable.

The FTA also suggests that there be conformity between parameters used in transit path selection and mode choice utility expressions for transit choices. That is, the path building process must weigh the various travel time and cost components in a manner that is consistent with the relative values of the mode choice coefficients. The FTA requires that level-of-service estimates for transit (and highway) must:

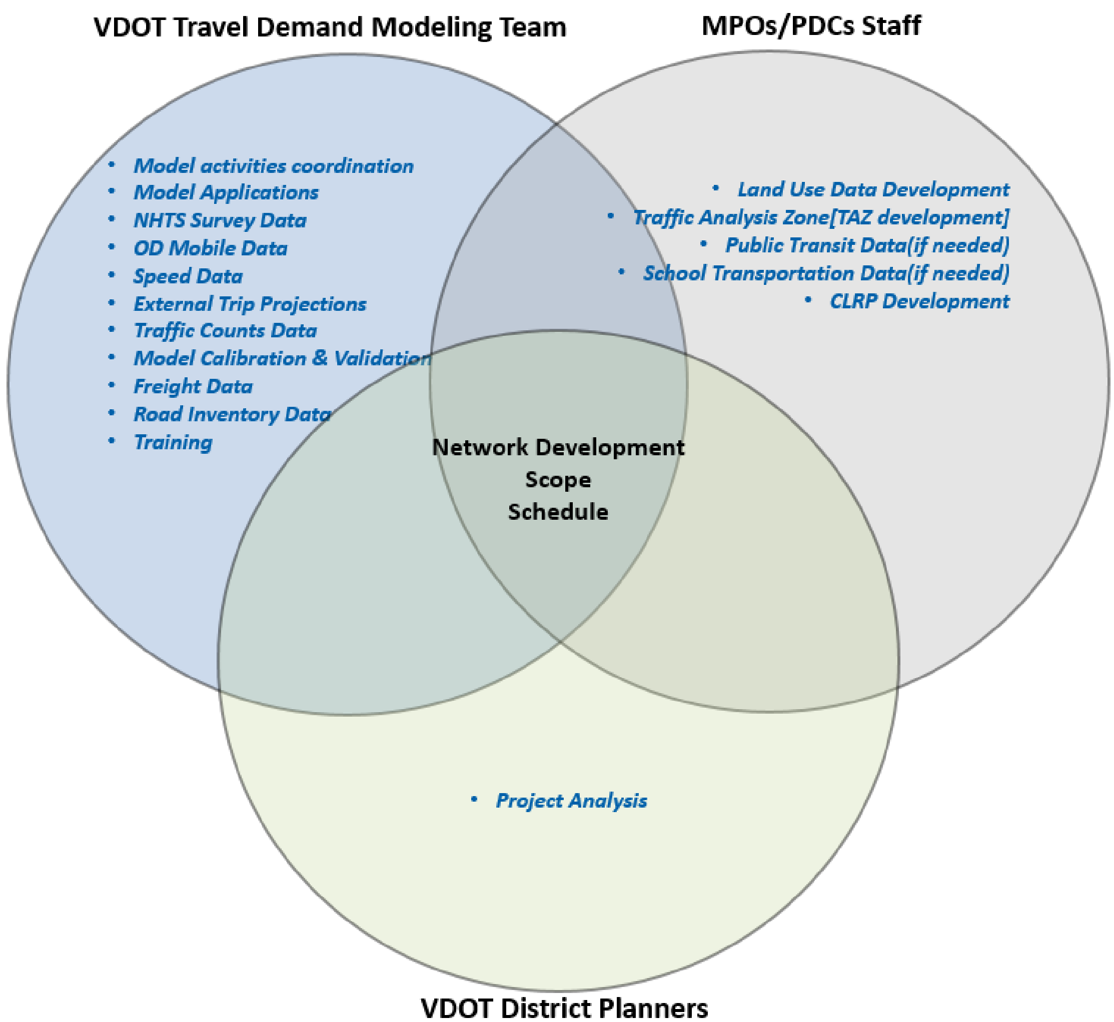
[1] This refers to the desirability of having conformance between parameters in transit path selection and the mode choice utility expressions for transit choices (e.g., coefficients on in-vehicle time and out-of-vehicle time).

- Replicate current conditions reasonably well;
- Predict defensible deltas by comparing conditions today versus the future; and
- Predict defensible deltas when comparing conditions across alternatives.

1.3 VDOT's Role and Responsibility in Supporting Modeling

As illustrated in Figure 1.3, VDOT Transportation Mobility and Planning Division (TMPD) staff, VDOT District Planners, and MPO/Planning District Commission (PDC) staff all play varying roles in the development, maintenance, and application of travel demand modeling in the Commonwealth of Virginia. All of these stakeholders are active in performing model application and traffic forecasting.

Figure 1.3 Virginia Travel Demand Modeling Stakeholder Responsibilities



The VDOT modeling group is based in VDOT's Central Office location in Richmond and is responsible for establishing statewide modeling policies and procedures and for the development and maintenance of the statewide model and all urban travel demand models except those in the Northern Virginia Region. The Central Office currently is responsible for 11 urban models located throughout the State, the Richmond/Tri-Cities/Hampton Roads Superregional Model, and the Virginia Statewide Transportation Model (VSTM).

Urban models maintained by VDOT staff are shown in Figure 1.4 and Table 1.3.

Figure 1.4 Virginia Travel Demand Modeling Regions by Areas of Responsibility

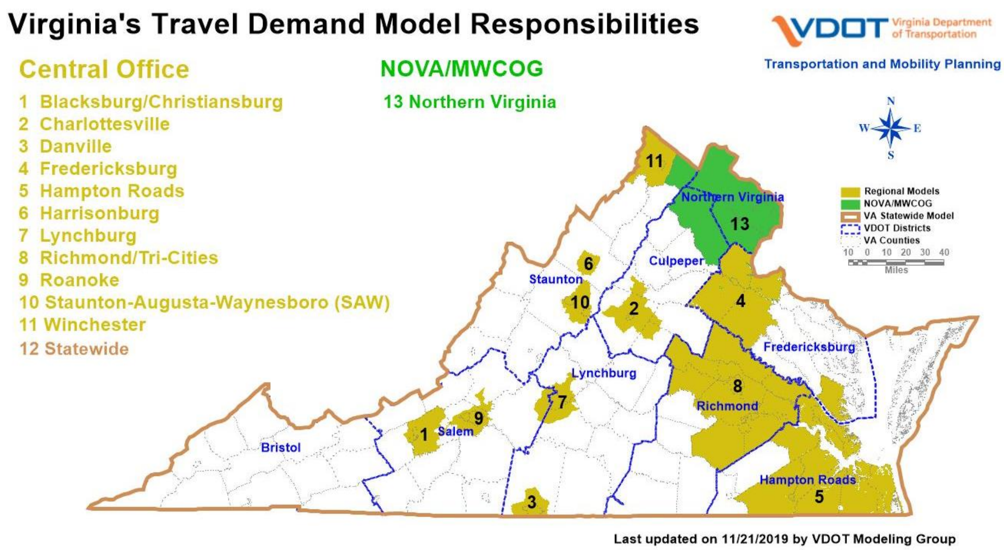


Table 1.3 Existing Urban Travel Demand Models

Model Region	Area (Sq. Miles)	Number of TAZs
Hampton Roads	2997	1173
Richmond/Tri-Cities	3028	1203
Fredericksburg	1417	794
Roanoke	246	205
Lynchburg	353	278
Charlottesville	430	289
Winchester	424	169
Blacksburg	347	310
Danville	198	166
Harrisonburg	106	236
Staunton-Augusta-Waynesboro (SAW)	229	305

Source: VDOT, 2020.

1.4 Purpose and Use of Policy and Procedures Manual

The Commonwealth of Virginia is the 12th most populous state with a population of over 8 million population[2] [5] and is experiencing rapid growth and increasing traffic congestion in many urban areas. As a result, the need for additional and more sophisticated models to serve Virginia's transportation planning requirements has grown in recent years. More development and congested travel have resulted in a greater need for consistency in model development and the requirement for guidelines on acceptable modeling practice. The purpose of this manual is to establish specific and uniform modeling policy and procedures for the Commonwealth of Virginia for use in model development and application by VDOT, MPOs, PDCs, and their consultants. This manual applies to all models in the Commonwealth of Virginia used for MPO planning activities with the exception of the three multistate MPOs whose central cities lie outside Virginia. These are the following:

- National Capital Region Transportation Planning Board (TPB), the MPO for the Washington, D.C. metropolitan area;
- Bristol Metropolitan Planning Organization (Bristol, Tennessee); and
- Kingsport Metropolitan Planning Organization (Kingsport, Tennessee).

For the Northern Virginia District area, TPB staff maintains the MPO model, and VDOT Northern Virginia District Staff have historically maintained modeling tools used for subarea studies in the Virginia part of the region. The cities of Bristol and Kingsport provide the support necessary to maintain the models in their respective MPO regions.

Throughout this manual, modeling practices are defined as "acceptable practice" or "recommended practice." *Acceptable practice* represents the minimum benchmark for modeling in Virginia and applies to all existing models; it can apply to future models if resources do not permit meeting recommended practice guidelines. *Recommended practice* is the preferred benchmark of practice and should apply to all future model updates if resources permit. In some cases, *unacceptable practice* may be cited if practices that are sometimes used or have been typically used in the past are now considered unacceptable.

Additionally, a distinction between small and large model regions is made for both acceptable and recommended practice. In the context of this manual, "small model regions" are model regions with less than 500,000 population which do not overlap with any large model region. "Large model regions" are 1) metropolitan statistical areas (MSA) of population greater than or equal to 500,000 or 2) have at least 200,000 population and are part of a MSA with a population of more than 500,000.

Large model regions require that transit travel be explicitly modeled, although transit may be modeled in small regions if the model needs to be used for planning of transit operations or improvements, or the effects of policies and projects being modeled have the potential for significant mode shifts. The sections of this manual pertaining to the modeling of transit,

[2] 2019 U.S. Census Bureau estimate is 8,535,519. 2010 U.S. Census Bureau figure is 8,001,024.

therefore, may not need to be referred to by readers dealing with models in smaller regions. The sections that may be unnecessary for these readers include:

- "Transit Networks" under Section 4.1.3;
- "Transit Rider Survey" under Section 4.2.1;
- Section 4.2.5, Transit Ridership Counts;
- Chapter 9, Mode Choice;
- Section 10.2, Transit Assignment Practice;
- Section 10.4, Transit Network Skimming; and
- Section 10.6, Transit Assignment Validation.

Table 1.4 displays the existing small and large model regions in Virginia. All large model regions have more than 500,000 population with the exception of Fredericksburg which is included in the large category because it is part of the MSA for Washington, D.C. It should be noted that all of the MSAs for large model regions in Virginia have populations greater than 1 million, meaning that Virginia currently has no model regions in the 500,000 to 1 million population range.[3]

Table 1.4 Existing Small and Large Model Region in Virginia

Small Model Regions <500,000	Large Model Regions >500,000
Roanoke	Hampton Roads
Lynchburg	Richmond/Tri-Cities
Charlottesville	Fredericksburg[4]
Winchester	
Blacksburg-Christiansburg	
Danville	
Harrisonburg	
Staunton-Augusta-Waynesboro (SAW)	

[3] Although *National Cooperative Highway Research Program Report 716* [3] discusses a few MPO size categories, the two-level stratification is deemed satisfactory for the situation present in the Commonwealth of Virginia.

[4] Fredericksburg had a 2010 population of 327,773 and is classified as large because it is part of the Washington, D.C. MSA.

1.5 Organization of the Manual

The remainder of this policies and procedures manual is organized to provide coverage to a variety of important modeling topics.

Chapter 2 describes how travel demand models are used in Virginia and the processes for developing and updating the models and for coordinating with VDOT. Chapter 3 describes the data used as inputs to the model as well as the data used for model development and validation. The main sources for the data are discussed in this chapter. Chapter 4 provides an overview of the model validation process. Further details about model validation are provided in later chapters dealing with specific model components.

Chapters 5 through 11 deal with individual components of travel demand models – trip generation, trip distribution, modeling external travel, truck and commercial vehicle travel, mode choice, trip assignment, and feedback loops, respectively. The mathematical processes used in the model component, the guidelines for performing a model step in Virginia, and an overview of model validation for the component is provided in each of these chapters.

Chapter 12 discussed model documentation and the requirements in Virginia. Chapter 13 describes the process for applying models in Virginia. A list of references is provided following Chapter 13.

The appendices include several pieces of important information related to modeling in Virginia. Appendix A contains the language from Code of Virginia 15.2-4202, pertaining to population estimates. Appendix B contains Code of Virginia 15.2-4208 which prescribes the general duties of PDCs. Appendix C provides complete citations of applicable federal law pertaining to modeling in Virginia. Appendix D includes the EPA designations for the Washington region. Appendix E provides a glossary of travel demand modeling terms used in this manual. A list of current VDOT staff modeling contacts is provided in Appendix F. Appendix G has the Travel Model Data Request Form for Virginia. Appendix H provides VDOT's Travel Demand Model Application Checklist. Appendix I presents a list of web sites pertinent to travel demand modeling in Virginia.

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CHAPTER 2. TRAVEL DEMAND MODEL USAGE IN VIRGINIA

This chapter describes in general terms the ways that travel demand models are used in Virginia.

2.1 Purpose and Need for Modeling in Transportation Planning Analysis

Travel demand models can be useful technical tools in many types of transportation planning analyses. Some examples of planning procedures where models can provide relevant information include:

- Evaluation of transportation system performance;
- Long-range transportation planning, including the development of transportation plans for metropolitan areas and states;
- Short-range transportation planning, including the development of Transportation Improvement Programs (TIP);
- Air quality conformity analysis;
- Evaluation of transportation improvements and infrastructure investments for highways, transit systems, and pedestrian or bicycle facilities; and
- Evaluation of the effects of transportation and planning policies (such as pricing and land use).

Models require resources to develop, apply, and maintain, including staff time, hardware and software, data, and other costs. When considering model development, updates, or improvements, planning agencies should carefully weigh the development and maintenance costs. For small urban areas, other technical and sketch planning tools for traffic forecasting may sometimes be considered in place of a model.

2.2 Type of Model Needed

As noted in Chapter 1, the most common type of modeling used in transportation planning applications is the four-step approach. In areas where only highway travel is analyzed, a "three-step" approach, omitting the mode choice component, may be used. Currently, all models in Virginia use a four-step or three-step approach and this is considered both **acceptable practice** and **recommended practice**. Activity-based and tour-based models, considered more-sophisticated practice, are employed in a few locations outside Virginia (mainly large urban areas) and could find use in Virginia at some point in the future.

2.3 Model Specification

Model specification refers to a model's structure, features, and capabilities. Models should be specified to meet the transportation planning analysis needs for the study area in the foreseeable future while being cost-effective and practical for application. For example, a sophisticated model able to analyze the impacts of tolls, HOV lanes, and various transit options makes good sense for a large urban area but probably is overkill for a small urban area with limited transit and no expectations for toll or HOV lanes.

2.4 Types of Model Improvements

Model improvements include a broad range of different types of model changes, from creating new models to correcting minor errors with model inputs and scripts. As discussed in Section 1.3, VDOT has two modeling staff groups, Central Office and Northern Virginia. Each staff group is responsible for model improvements to models that they maintain. This section classifies model improvements into the three categories shown in Table 2.1: model development, major revisions, and minor revisions. Table 2.1 also shows the scope, implementation frequency, and examples of each type of model improvement. The list of examples is not an exhaustive list, but, rather, a representative sample.

Table 2.1 Classification of Types of Model Improvement

Type of Model Improvement	Scope	Frequency	Examples
Model Development	Changes to structure which require updates to input data and extensive validation and calibration	At least once every 10 years	• Recalibrate model based on new survey data • New trip generation model • New trip distribution model • New mode choice model • New trip assignment model
Major Revisions	Adding modules or revising inputs or parameters with only minimal changes to structure. Validation and calibration are required.	Review for need at least once every five years and perform as necessary	• New volume-delay function • New speeds/capacities • New trip purpose(s) • New truck model • New toll model • New GIS-based network • New vehicle occupancy rates • New trip rates • Incorporate time of day
Minor Revisions	Minor changes to correct errors and update model inputs and files based on the latest assumptions. Some validation may be required.	Review for need annually and perform as necessary. Should be performed in advance of major model applications.	• Correcting land use errors • Correcting network errors • Correcting minor errors in model scripts • Updating networks based on revised short-term plan assumptions

2.4.1 Model Development

Model development is large scale in scope and is associated with the creation of new models or redevelopment of existing models and usually involves a new "base year" for the model. Model development involves extensive validation and calibration efforts based on data sources for the new base year. It is desirable for the base year to change at most every 10 years because trip making characteristics and demographics can change rapidly, especially in larger urban areas and rapidly growing regions.

The model development process should be coordinated with the availability of major Federal data sources such as the decennial U.S. Census and local and national survey data sources (see Chapter 4). Model development should also include a review and update of TAZs and updates to the major data inputs, namely the socioeconomic data and the transportation networks. Data used for model validation, including surveys and traffic and transit ridership counts, should also be current to the new base year. The use of new data and potentially a revised model structure means that the model parameters will be updated in the model development process.

Model development can be time- and resource-intensive and requires extensive data collection and analysis. As such, model development efforts should be done separately from other transportation planning activities. To avoid project schedule issues, the timing of model development efforts should not coincide with or occur immediately before major model applications.

2.4.2 Major Revisions

Major revisions are medium scale in scope and may include adding new modules to existing models, such as a new truck model or incorporation of time-of-day analysis, or significant revisions to model inputs or parameters. Major revisions can result in some minor changes to model structure and generally require the revised model to be revalidated. The major difference between major revisions and model development is that major revisions do not result in significant changes to the model structure.

Each model should be reviewed by the VDOT designated modeler at least once every five years to determine whether a major revision is needed before the next model development effort. The necessary model revisions should incorporate updated model input data (land use/socioeconomic data and transportation networks) as well as updated data for validation. Model updates should be completed for use in all large-scale model applications such as MPO long-range plans and corridor studies. By the conclusion of the MPO long-range planning process, model transportation networks and other components should be updated based on the adopted long-range plan.

2.4.3 Minor Revisions

Minor revisions are relatively small updates to model inputs and files needed to correct minor errors in model input data or changes in model assumptions, such as the list of projects included in short-range plans. The VDOT designated modeler continuously maintains a list of minor changes that need to be included in the next model revision. The VDOT designated modeler reviews this list annually in light of known upcoming model applications. If a major model application will be done in the next year, a minor revision should be performed on the model in advance of the upcoming application. Examples of major model applications include:

1. MPO Long-Range Transportation Plan;
2. District Short-Range Plan (TIP);
3. Air Quality Conformity; and
4. Project Prioritization Studies.

If no major model application is coming up in the next year, the project manager should make a judgment on whether or not the revision is needed at that particular time.

2.5 Model Improvement Process

2.5.1 Version Naming System for Model Improvements

The Virginia version naming system for the three types of model improvements documented in the previous section is illustrated in the example in Table 2.2. Model development initiates a new version name with this format: "Base Year" Version 1.0. For example, a new model created with a 2000 base year would be called Base 2000 Version 1.0. Major revisions and minor revisions cannot change the base year, but alter the version number. A major revision causes the version number to increase to the next integer. For example, a major revision to the Base 2000 Version 1.01 model, would result in a new model called Base 2000 Version 2.0. Minor revisions simply increase the version number in increments of one-hundredth. For example, a new minor revision to the Base 2000 Version 1.0 model, would result in a new model called Base 2000 Version 1.01.

Table 2.2 Example of Version Naming System for Types of Model Improvements

Type of Model Improvement	Original Base Year	Year of Model Improvement	Version Names	Version Numbers
Model Development	2020	2022	Base 2020 Version 1.0	2020.1.0
Minor Revision	2020	2023	Base 2020 Version 1.01	2020.1.01
Major Revision	2020	2025	Base 2020 Version 2.0	2020.2.0
Minor Revision	2020	2027	Base 2020 Version 2.01	2020.2.01
Minor Revision	2020	2028	Base 2020 Version 2.02	2020.2.02
Major Revision	2020	2029	Base 2020 Version 3.0	2020.3.0
Minor Revision	2020	2030	Base 2020 Version 3.01	2020.3.01
Model Development	2030	2032	Base 2030 Version 1.0	2030.1.0
Minor Revision	2030	2034	Base 2030 Version 1.01	2030.1.01

2.5.2 Request Process for Model Revisions

If a VDOT district, MPO, or PDC desires that a model serving their area undergo model development, major revision, or minor revision, staff should contact the appropriate VDOT staff member to discuss the agency's needs. A list of staff contacts for the different modeling areas in Virginia is shown in Appendix F.

2.5.3 Creation and Expansion of Models

If a VDOT district, MPO, or PDC that is not served by any existing model desires that a new model be created for their planning area, they should first contact the VDOT designated modeler to discuss their needs. If the planning area is adjacent or close to the area for an existing model, it is preferable to expand the existing model to include the additional planning area. For example, if the planning area is in a county whose neighboring county is part of an existing model, it makes sense to expand the existing model to include this planning area and areas in between. For rural areas, transportation planning needs could potentially be addressed through the use of the Virginia Statewide Transportation Model (VSTM) or other technical tools.

For instances where a VDOT district, MPO, or PDC desires that an existing model be expanded to include a new area, the following guidelines exist:

1. Expansion should only include entire jurisdictions;
2. Data needed to support the model expansion should be available using existing funding and resources; and
3. New jurisdictions added to the model should be within the boundaries of Virginia unless approval is obtained from MPOs, local jurisdictions, and state DOTs affected in any of the states or districts adjacent to Virginia.

2.5.4 Requesting Travel Demand Model Data and Files

Travel demand model data and files can be requested from VDOT staff using the Travel Model Data Request Form. Except for MPO staff, model data and files cannot be obtained without filling out this form. This form is available on the VDOT intranet site and is in Appendix G of this document. For questions regarding this process, contact the VDOT designated modeler.

2.6 Consideration of Emerging Transportation Modes and Trends

Over the past several years, a number of new mobility questions have come to the forefront of transportation planning as the result of new emerging modes of travel and other emerging trends in travel patterns. Addressing these questions typically requires the ability to examine them in a reasonably accurate way in travel demand models. Emerging mobility questions faced in this context include the following:

- Transportation Network Companies;
- Shared Micromobility Options; and
- Connected and Autonomous Vehicles.

In this section, some of the key modeling considerations that are required to analyze these emerging questions are addressed.

2.6.1 Transportation Network Companies (TNCs)

Transportation Network Companies (TNCs) are rideshare companies like Lyft and Uber that provide "prearranged rides for compensation using a digital platform that connects passengers with drivers using a personal vehicle. TNC drivers are referred to as TNC partners." [6] TNCs are required to obtain a certificate of fitness through Motor Carrier Services at the Virginia Department of Motor Vehicles (DMV), prior to offering or engaging in TNC services within Virginia. Only vehicles registered for personal or authorized rental use qualify to be used as a TNC partner vehicle, but they are not required to be registered with DMV to provide TNC services in Virginia.

TNCs has gained popularity since their introduction in 2011. According to Pew Research Center surveys in 2015 and 2018, the share of Americans who used TNC services like Uber and Lyft had increased dramatically, from 15% in 2015 to 36% in 2018, while the share of respondents who had not heard of these services decreased significantly from 33% to 3% [7]. TNC usage has increased across most demographic groups, but adoption rates tended to be the highest among young adults, college-educated, high-income, and urban residents. Based on a 2016 survey conducted in Northern Virginia, Richmond, and the Hampton Roads/Tidewater area by Virginia Tech's Center for Survey Research, 34% of respondents in Virginia used TNCs like Uber and Lyft, and 71% were familiar with these services. TNCs were introduced in Northern Virginia in 2011 and in Richmond and Hampton Roads in 2014 [8]. TNC usages or adoption rates in Virginia varied by similar demographic characteristics, consistent with those revealed from the national surveys conducted by Pew Research Center.

The emergence of transportation network companies (TNCs) has had a big impact on how people travel in many regions. TNCs provide taxi-like service, but at a lower cost and more widespread, making them more accessible to a larger portion of the population than taxi services. Shared mobility options among TNC services offer even lower costs with even wider accessibility, though these services may be less attractive in some cases due to higher travel times and mobility limitations of some travelers. A study of Uber and Lyft data for September 2018 showed that TNCs accounted for an estimated range of 1.0 - 2.9 percent of total VMT for the six metropolitan regions, including Boston, MA; Chicago, IL; Los Angeles, CA; San Francisco, CA; Seattle, WA; and Washington, DC [9]. TNC shares of total VMT in the core areas of these regions are higher, ranging from around 2 percent to over 13 percent of total VMT.

From a modeling perspective, TNCs operate in a way similar to taxis. There are three key considerations when analyzing TNCs in a model framework:

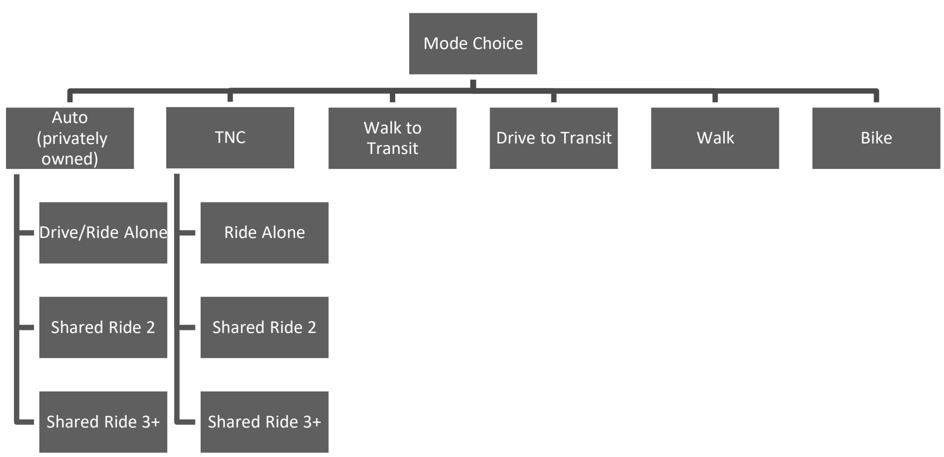
- Similar to taxis, the TNC passenger mode can be handled well within a traditional modeling framework as a mode within the mode choice model. It is important to consider the unique characteristics of the TNC mode. While zone to zone travel times may be borrowed from other auto modes, TNCs have other unique attributes including wait times, terminal times, fares, and relative levels of accessibility across geography.
- TNC fares represent another critical element of consideration. Unlike traditional taxis, which have fixed fare structures related to trip distance or zone definitions, TNC fares vary widely depending on demand and supply levels (e.g., surge pricing) and by type of service (e.g., shared services). While it may not be feasible to account for the actual fare structures used by TNC operators in the model, the fare structures of TNCs should be analyzed carefully on a region-by-region basis and professional judgment is needed to make reasonable assumptions that can be used in a model. TNC fare information can typically be found in the data released by TNC operators in the cities where TNCs were required to publicly report their trip data, e.g., Chicago [10]. A study of Chicago TNC data for five months in 2018-2019 indicated that non-pooled TNCs offered significantly lower fares per mile than taxis and their rates were fairly consistent throughout the City, unlike taxis which had higher fares per mile in downtown areas than the other areas in the City [11].
- Another critical element for incorporating TNCs in a model is dealing with re-positioning trips between drop-off of one customer and pick-up of the next. While

such trips are typically ignored if taxis are considered in a model, these re-positioning trips are more important for TNCs because there are so many more of them on the roads than taxis. Based on a study of Uber and Lyft data for September 2018, approximately one third of TNC vehicle miles were attributed to a driver waiting for a ride request, approximately 10 percent to a driver heading to pick up a passenger [9]. No standard approach yet exists for incorporating these trips in travel demand models, but approaches based on creating trips between TNC trip ends are the most theoretically appealing. However, even these methods ignore two important potential features of TNC re-positioning trips:

- First, it may not be possible to account for re-positioning trips that do not have a clear destination, that is, if the driver continues travel on the network even without having a destination point. These types of trips probably cannot be modeled in any way but may be small enough in number to not worry too much about.
- Second, since many travel demand models do not have an explicit visitor model component and visitors make up a disproportionate share of TNC passengers in a region, the overall levels of re-positioning trips may be vastly underestimated. Explicit representation of visitor travel in the model can improve model performance.

Figure 2.1 provides an example of incorporating TNCs into a mode choice structure in the Colorado statewide model [12].

Figure 2.1 An Example of Mode Choice Structure with TNC



Source: Cambridge Systematics, Inc., "CDOT StateFocus: CAV and TNC Enhancements," 3-5, Figure 3.1, 2019 [12].

This model is sensitive to the following person or trip characteristics, as it relates to the TNC option:

- Trip purpose and time of day;
- Household income;
- TNC travel cost, where costs assume a minimum flat fare plus a distance-based additional fare;
- TNC travel time, with initial wait times varying by area type or TAZ; and
- Availability of vehicles in the household.

A procedure was implemented to balance the TNC demand trip table, which would include zero-occupant vehicle trips between pick-ups and drop-offs.

In order to calibrate the model appropriately for TNCs, observed data are needed. One robust dataset for national level trends is the National Household Travel Survey (NHTS), which can provide detailed information related to usage patterns by demographics and by land use or area type patterns. It can also provide overall national rates of TNC usage, though these should only be used as a benchmark, since TNC usage varies considerably from one geographic area to another.

The best type of data for understanding overall TNC usage in a region comes from TNC operators, but unfortunately, these data are not widely available in most places. TNCs were required to publicly report their trip data in a limited number of cities, including Chicago, New York, and Seattle. Increasingly, more cities have released disaggregate TNC data. While recently collected local survey datasets typically collect only a small number of TNC samples due to the mode's relatively low mode shares, these data may provide the best indication of TNC usage at a local level. However, it is important to remember that household travel surveys typically only collect data from residents, but visitors represent a disproportionate share of TNC trips. As a result, TNC rates may need to either be inflated in the model calibration process or visitors should be represented explicitly in the model.

In the 2017 NHTS, TNCs were included as part of mode for taxi/limo, including Uber and Lyft. The weighted modal share for taxi/rideshare was 0.47% on a weekday, in comparisons with 0.2% modal share for car rental/carshare.

In addition to the typical household travel survey trip data, the following question was asked of respondents (those of at least 16 years of age):

> *"In the past 30 days, how many times have you purchased a ride with a smartphone rideshare app (e.g., Uber, Lyft, Sidecar)?"*

Table 2.3 summarizes the responses to this question for the entire dataset nationwide. Virginia had approximately 600 sampled households in the 2017 NHTS, which could provide a glimpse of TNC travel, but it is such a small sample that it may be a challenge to use to represent a general population in terms of its TNC usage, which took a really small modal share in 2017. In addition, the TNC has evolved rapidly since 2017. The upcoming NHTS Add-On program in which Virginia participates is expected to provide a larger sample and thus will provide a better representation of the TNC travel in the Commonwealth.

Table 2.3 2017 NHTS Rideshare App Use in Past 30 Days

Rideshare App Use (Times per Month)	Nationwide			
	Unweighted		Weighted	
	Persons	Percentage	Persons	Percentage
0	246,551	93%	276,271,841	92%
1	4,942	2%	6,245,758	2%
2	4,413	2%	6,128,432	2%
3	1,779	1%	2,544,664	1%
4	1,612	1%	2,485,143	1%
5	1,456	1%	2,458,909	1%
6	769	0%	977,803	0%
7+	2,376	1%	4,017,215	1%
Total	263,898		301,129,765	
Overall Average per Person			**0.01126**	

Source: Cambridge Systematics, Inc., analysis of 2017 National Household Travel Survey.

TNC studies revealed common characteristics on TNC users including higher education, higher income, younger, urban, or high-density residents, and those with no vehicles in the household [13]. Little consistent information is available on the types of trips that are being made with TNCs. A survey from the Metropolitan Area Planning Council (MAPC) in Boston revealed three most popular activities for TNC trips originating from home: work, entertainment, and social visit [14].

In a recent study, publicly available 2018 rideshare data from Chicago and New York City were explored to investigate the potential use of these data for development of a predictive model [15]. Simple regression based trip generation models were estimated for both cities. The exogenous variables were used to predict the generated TNC trip at a Census Tract (for Chicago) or TAZ (for New York City) level. The model estimation results identified the statistically significant variables, including population and employment density, access to major transit centers, median household income, and the presence of college campuses.

The Puget Sound Regional Council (PSRC) conducted a regional household travel survey in 2015 and 2017, asking how often the respondent used ridesharing and carsharing. A study by Dias et al. (2017) made use of the 2015 household travel survey and estimated the propensity of the survey responder to fall among one of these categories by regressing the indicator variables using a multivariate probit modeling method [13]. The variables found significant in determining the frequency of use of carshare and/or TNCs were age, education level, employment type, smartphone ownership, household size, average income, and number of vehicles owned by their respective households.

Table 2.4 shows a summary of TNC trips per day for select cities and regions where data are available [16].

Table 2.4 Estimates of TNC Trips per Day for Select Cities or Regions

Geography	Year of Estimate	Population	Number of TNC Vehicle Trips per Day	Average TNC Trips per Person	Source
Seattle	2018, Quarter 2	3,940,000	91,200	0.02	Gutman (2018) **[17]**
San Francisco (Intra)	2016 (Weekday)	876,000	170,000	0.19	San Francisco County Transportation Authority (2017, 2018) **[18]**, **[19]**
Boston	2017	685,000	95,600	0.14	Gehrke et al. (2018) **[14]**
Massachusetts	2017	6,863,000	177,500	0.03	Gehrke et al. (2018) **[14]**
Chicago	Nov 2018-Mar 2019	2,706,000	286,000	0.11	Roy et al. (2020) **[11]**
New York	2018	8,399,000	650,000	0.08	Momtaz et al. (2020) **[15]**

Source: Adapted from Cambridge Systematics, Inc., "CDOT Emerging Mobilities Impact Study," 3-23, Table 3.16, 2019 [16].

Notes: Where annual TNC trips were available, a factor of 1/365 was applied to estimate daily trips.

It is important to recognize that TNCs are still gaining in market share and a great deal of uncertainty still exists on how much people will embrace this mode for regular use. As a result, it is important to recognize that assumptions about this mode may need to be updated regularly, either through regular monitoring of usage patterns or some other metric. TNC mode constants can be adjusted to reflect changes in usage patterns.

Given the lack of local data for TNCs, it is **acceptable practice** for all MPO areas not to include TNCs in their models in the short term, and instead, use the TNC trip rates from the latest NHTS data or data from similarly-sized cities elsewhere in the country to derive a range of TNC trip estimates. When the new NHTS Add-On data for Virginia are available, it is **acceptable practice** and **recommended practice** for MPO areas to use the NHTS Add-On for Virginia to estimate TNC trips and **recommended practice** for large MPOs to consider incorporating the TNCs as part of the model development process in the medium and long term.

2.6.2 Shared Micromobility Options

Shared mobility is defined to include a broad range of modes that have a shared use, such as shared bikes, scooters, and cars. Like TNCs, shared micromobility modes, including e-scooters and bike shares, have emerged over the last few years, impacting travel patterns in a variety of ways. These technologies have provided a new transportation mode option for many trips, especially short trips in urban areas where e-scooter and bike share availability is highest. Moreover, they are providing new options for first and last mile of transit journeys in many areas.

Incorporating these new modes into travel models is straightforward conceptually and can largely be accomplished by adding new modes to the mode choice model, much like TNCs. There are two mode considerations that might be considered:

- First, shared micromobility options might serve as the primary mode of travel, similar to TNC or bike mode.
- Second, shared micromobility modes might serve as access and egress mode options for transit services. In these cases, shared micromobility modes might be grouped to form a composite access or egress mode option for transit with disparate characteristics from walk or drive access and egress. If bike mode access is already included in the model, bike access could be expanded to include shared micromobility since mode speeds may be similar, though the mechanics of such an option might become too complicated since fares and accessibilities may be different.

The characteristics of shared micromobility modes are largely similar to the bike mode in terms of speed, though e-scooters may be prohibited from certain types of bike facilities like bike trails. However, these modes also include a fare component and availability or accessibility variables need to be included in the model to reflect the fact that availability of the equipment will vary by geography. If docking stations are required, then availability should depend on the locations of docking stations, while if dockless equipment is used, availability likely varies based on land use or area type.

Data to support model development and validation of shared micromobility options is even thinner than TNC data because shared micromobility modes have not been around as long. They also serve a trip market that is less well studied and understood. Shared micromobility modes tend to serve short trips in the urban core, which are typically non-home-based trips. Recent household travel survey datasets might be useful to support the identification of trip types using these modes, but sample size issues may be a problem for making generalizations. As these modes gain traction and usage rates climb, new survey datasets may have more robust samples. If shared micromobility companies are willing to share usage data publicly, these data would be invaluable to calibrating models.

Obviously, the use of shared micromobility mode is strongly dependent on provision of such services, which is currently still limited in a few places in Virginia in terms of bike share programs such as those in northern Virginia, Richmond, Roanoke, and Blacksburg, but evolving rapidly in terms of e-scooters. State and local regulations have recently emerged and evolved regarding these services. New Virginia legislation requires localities to regulate these shared mobility devices and will allow e-scooters even if localities do not adopt their own regulations, starting in 2020.

Given the current evolution of shared micromobility modes in Virginia and lack of local data, it is **acceptable practice** for MPO areas not to include shared micromobility modes in their models in the short term, and instead, focus efforts on data collections and use off-model processes to derive a range of shared micromobility trip estimates. When the new local data are available, it is **acceptable practice** and **recommended practice** for MPO areas to use the local data to estimate shared micromobility trips and **recommended practice** for large MPOs to evaluate the need to incorporate shared micromobility as part of the model development process in the long term. Like TNCs, market penetration rates of shared micromobility modes continues to climb, and uncertainty exists on where usage rates will equilibrate. Metrics should be developed and monitored on a regular basis to determine whether and how mode choice model variables need to be updated in the model.

2.6.3 Connected and Autonomous Vehicles (CAVs)

While connected and autonomous vehicles (CAVs) have not yet made their way onto roads, transportation professionals have been anticipating their arrival for several years. They promise to enhance the efficiency of the transportation system while offering improved accessibilities. There are a number of ways that CAVs may impact how people travel and/or the attributes associated with auto travel:

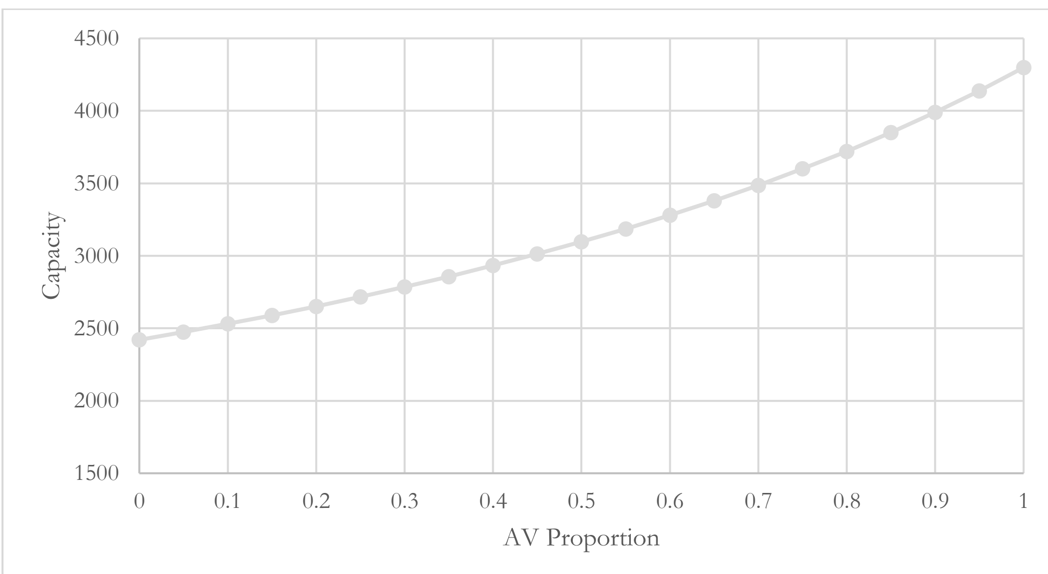
- Higher roadway capacities will be possible, especially on limited access highways, due to the ability of CAVs to coordinate movements. Studies show a wide variations for the CAVs' capacity improvement, varying by market penetration or proportion of CAVs in fleet on roadways, among other factors. Typical estimates of the capacity improvement range between increases of 50 to 100 percent [20], [21], [22], [23]. Capacities on arterials may be slightly improved with full CAV adoption, typically assumed to be 10 to 20 percent increase [20], [22], [23]. As an example based on a traffic flow model, Figure 2.2 shows capacity (vehicles per hour) at different proportions of autonomous vehicles, increasing more slowly at lower proportion of autonomous vehicles [24]. As another example based on simulation, Table 2.5 displays the maximum throughput for some combinations of market penetration rates of connected and autonomous vehicles; at low market shares, the impacts are relatively minor on either throughput or stability. However, as market shares increase, autonomous vehicles exert a greater influence on capacity and stability than connected vehicles [25], [26]. Figure 2.3 illustrates the capacity improvement factors for interstate facilities at different level of AV proportions in the travel, which were implemented in an Ohio travel demand model [25].
- Parking needs and costs may be reduced as CAVs can provide door-to-door service and find parking at off-site facilities. Typically parking costs are assumed to be reduced by 50 to 100 percent [20], [27].
- Individuals that are unable to drive themselves (e.g., disabled or children) may see improved accessibilities. In an activity-based model, this may mean expanding the

drive alone mode availability to children. In a trip-based model, this may mean increasing the drive alone mode constant slightly [28], [22].

- Traveler values of time may be reduced as a result of being able to use time spent in a CAV more productively (e.g., reading or working). Typical estimates of value of time reduction are in the range of 10 to 50 percent [20], [21], [22] [27], [28].
- Non-passenger trips (with zero occupants) will emerge to travel to/from parking. These require special procedures to generate these trips and add in assignment procedures [29], [23].
- Additional trips may be induced due to lower total costs of driving. Typical estimates of induced trips are on the order of 0 to 10 percent [29], [23].

This list is by no means exhaustive but seems to be the most common attributes that are accounted for in scenario analysis of CAVs. Other considerations may be the impact on auto operating costs, vehicle ownership, auto occupancy levels, among others.

Figure 2.2 Capacity on Freeway in Proportion to the Share of Autonomous Vehicles



Source: B. Friedrich, "The Effect of Autonomous Vehicles on Traffic, 327," Figure 16.9, 2016 [24],

$$C_m = \frac{v}{\eta v T_a + (1-\eta)\, v T_h + L_{Pkw}}.$$

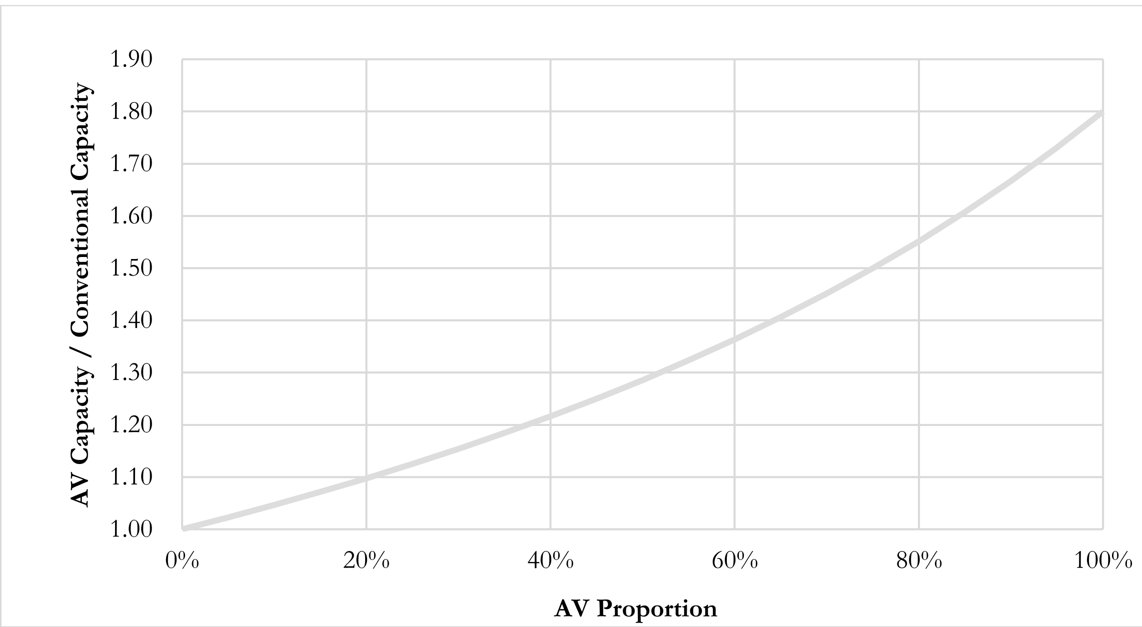
, where Cm = Capacity, η= Percentage of AVs, Ta = Headway AV (0.5s), Th = Average Headway (1.15s), v = Average Speed (80km/hr), L = Average Car Length (7.5m).

Table 2.5 Throughput (veh/h/lane) at Different Market Penetration Rates of Connected and Autonomous Vehicles

Regular vehicles	Connected vehicles	Autonomous vehicles	Average lane capacity, veh/hr
100%	0%	0%	1,800
50%	50%	0%	2,057
50%	0%	50%	2,400
0%	50%	50%	2,880
0%	100%	0%	3,600
0%	0%	100%	3,600

Source: P. Vovsha and G. Vyas, "Incorporating AVs in Ohio 3C CT-RAMP2 Model," slide 27, 2018 [25]; A. Talebpour, and H. S. Mahmassani, "Influence of Connected and Autonomous Vehicles on Traffic Flow Stability and Throughput," *Transportation Research Part C: Emerging Technologies*, 71, 143-163, 2016 [26].

Figure 2.3 Capacity Improvement Factors for Interstate Facilities

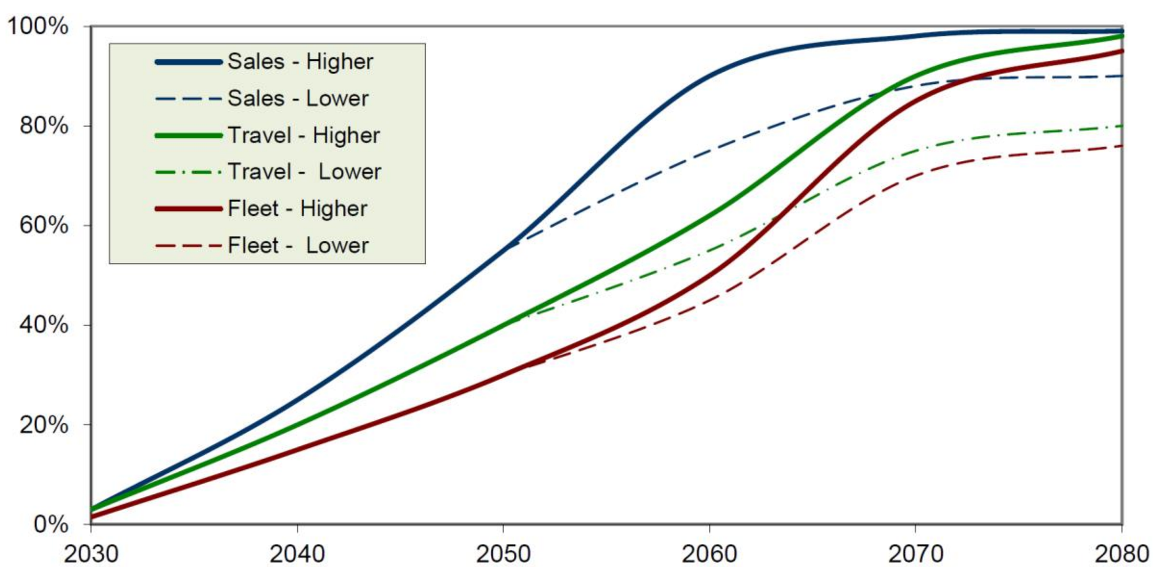


Source: P. Vovsha and G. Vyas, "Incorporating AVs in Ohio 3C CT-RAMP2 Model," slide 29, 2018 [25].

All of these considerations can be addressed in an activity-based model, and most can be addressed in trip-based models. Furthermore, the model can be designed so that these variables are inputs to any future scenario, allowing for ease in developing future model scenarios. However, because CAVs do not currently exist outside isolated testing environments, the impact that CAVs will have in each of these areas is unknown. Complicating matters, it will take time for the entire auto fleet to transition from non-CAV to CAV, resulting in a period with a mixed fleet. This is particularly important for predicting how roadway capacities will be impacted by the introduction of CAVs, since some believe that roadway capacities may actually be reduced at low market penetration levels in mixed fleet scenarios.

Adoption of the CAVs is expected to follow an S-curve development pattern historically exhibited for new technologies, with a gradual slow process at the beginning stages of development, testing, approval, and commercial release, and then at an accelerated pace for the stages of product improvement, market expansion, differentiation, and maturation, eventually reaching plateau at the stages of saturation and finally in decline. Similarly, there are five customer segments of technology adoption in the order of adoption: innovators (2.5%), early adopters (13.5%), early majority (34%), late majority (34%), and laggards (16%) [30]. Younger and higher income households are more likely to be adopters of new technology. CAV adoption rates are important assumptions for evaluating the CAV impacts on travel. Figure 2.4 shows predictions of autonomous vehicle sales, fleet, and travel over the fifty year horizon, based on the historical adoption of previous vehicle related technologies [31]. It can be seen that on the current planning horizon 2045, the AV sales are projected to take approximately 40% of the market penetration, 20% of vehicle fleet, and 30% of vehicle travel. By 2060s, the AV sales are expected to reach market saturation with 80-100% new sales, with 50-80% of travel being autonomous vehicles. This prediction is consistent with some predictions in the industry but less optimistic than others who forecast a steeper curve.

Figure 2.4 Autonomous Vehicle Sales, Fleet and Travel Projections



Source: T. Litman, "Autonomous Vehicle Implementation Predictions," 28, Exhibit 20, 2020 [31].

Existing trip-based models can be enhanced in different ways to incorporate the effects of CAVs, as shown in Table 2.6.

Table 2.6 Enhancing Trip-Based Models to Incorporate Effects of CAVs

Model Components	Model Enhancement Options
Socioeconomic models	Add estimation of the expanded mobile population (currently non-drivers) CAV adoption rates vary by household income, householder age, and household type
Vehicle availability/ ownership model	Add CAV availability or ownership as a choice option
Trip Generation	Adjust trip rates by the expanded mobile populations Estimate zero-occupant vehicle trips Adjust trip rates by other CAV-inclined population
Trip Distribution/ Destination Choice Model	Adjust the composite impedance function to incorporate new sensitivity to CAV travel time Adjust coefficients for level of service variables in the destination choice model to represent effects of CAVs on trip length
Mode Choice Model	Add CAVs mode(s) to the auto mode alternatives and as options for transit access/egress modes, with in-vehicle time coefficients asserted to reflect improved perception of the value of travel time in CAVs Prepare CAV-specific inputs to mode choice model, including reduced parking costs
Trip Assignment	Provide capacity assumptions for CAV-dedicated guideways and mixed flow facilities to reflect the CAV effects Assert value of time for CAV trips in a generalized cost function

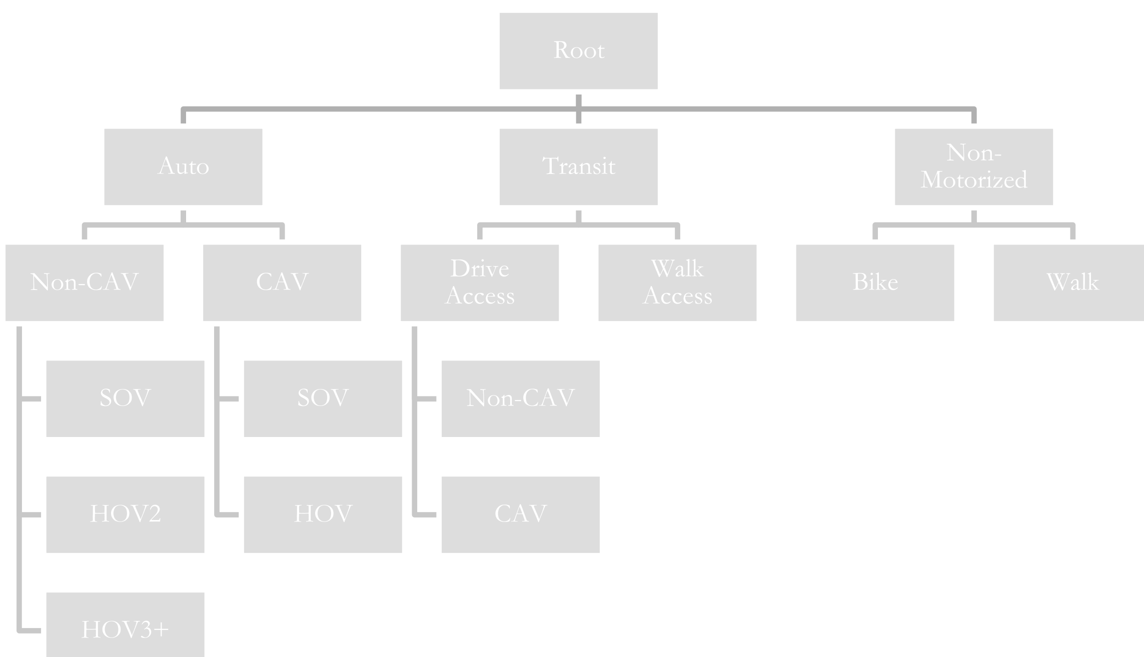
Source: Cambridge Systematics synthesis of literature.

Best practice for modeling CAVs involves several steps including the following:

- Segment the population into CAV-inclined and CAV-declined to distinguish the population segments that are likely to adopt and benefit from CAVs. The population in each should be based on an input decided by the analyst. The input might be the direct CAV-inclined percent of the population, or it might be the CAV market penetration rate, which could be different since different populations might generate different levels of trips and use modes at different rates. CAV adoption rates could vary by household income, householder age, and household type, based on a CAV adoption likelihood matrix [12]. An auto availability or ownership model can also include options for a CAV, but the challenge is the lack of data to estimate model coefficients, which have to rely on assertions or estimated using a stated preference survey.

- CAV-inclined populations are assumed to derive the benefits of CAVs as outlined above (e.g., reduced value of time, reduced parking costs, greater reliance on drive alone modes, and potentially increased trip rates). In trip generation, estimation of trips needs to incorporate the expanded mobile population—those currently non-drivers (the young, elderly, and disabled) or vehicle insufficient households, and zero-occupant vehicle trips. In trip distribution and destination choice models, sensitivity to impedance needs to be adjusted to reflect the effects of CAVs. In mode choice models, CAVs mode can be added as part of the auto mode options and as an option of access/egress modes, with in-vehicle time coefficients asserted to reflect the improved experiences of travel for the CAVs mode. Figure 2.5 shows an example of mode choice model with CAVs.
- CAV-declined populations are assumed to have no change in sensitivities.
- Non-passenger trips should be modeled as a function of the CAV-inclined trips and home and attraction ends of those trips.
- Freeway capacities are assumed to be some function of market penetration. As noted above, freeway capacities may actually be reduced at low market penetration levels. If dedicated facilities are included in the network for CAVs, capacities on those facilities would enjoy full benefits of capacity reduction by CAVs. Capacities on non-freeways may also be impacted, especially if CAVs are fully adopted, but best practice typically does not consider any arterial capacity improvements for mixed fleet traffic.

Figure 2.5 An Example of Mode Choice Structure with CAVs



It is worth noting that other practices for modeling CAVs may be acceptable or even preferable depending on the circumstances and resources available. It is also worth noting that a great deal of uncertainty exists with CAVs. Therefore, scenario testing and/or exploratory modeling may be used to provide a more robust set of outcomes that better reflect the overall levels of uncertainty.

Different regions have different planning needs to address the potential impacts of CAVs. If it is one of the region's top priorities to evaluate the impacts of CAV on travel in the long range planning process, the regional travel demand model can be adapted to assess these impacts. It is **acceptable practice** to take a scenario approach to modeling the CAVs, using a representative range of values for key assumptions, including market penetration of AV travel, adoption rates by market segmentations, travel benefits in reduced value of time, parking costs, expanded mobile population, and roadway capacity improvements.

2.7 Uncertainty in Travel Demand Models

It is well established that there is a substantial amount of uncertainty around the results of travel demand models [32], [33]. This uncertainty begins with the model inputs, which can include measurement or sampling errors. The uncertainty surrounding model inputs is even greater when a scenario representing a future time period is being modeled since the inputs represent as-yet unobserved forecasts of socioeconomic data, policy decisions, and other factors affecting travel behavior.

Uncertainty is also a concern related to the model structure and parameters. A model is necessarily a simplification of the myriad of factors that affect travel behavior of a diverse population, and the model developer makes numerous choices regarding model structure, variables used, and sources of parameters (estimation from various data sources, transfer, and/or assertion). There is a great deal of uncertainty associated with the data used to estimate model parameters. Even when parameters are estimated from robust data sources, there is parameter uncertainty related to the statistical methods used for estimation, even though the estimates generally reflect maximum likelihood. It is also important to note that the choice of input variables is limited to what can be feasibly collected or forecast. Many factors that undoubtedly affect travel behavior are omitted from models because they cannot be quantified or forecast, leading to further uncertainty in model outputs that do not consider these unincluded variables.

The interest in uncertainty in model results has increased recently due to the rapid changes happening in mobility, including transportation network companies (TNCs) and micromobility, as well as future transformative changes related to connected and autonomous vehicles (CAV). These changes increase the uncertainty associated with travel demand forecasts.

Most travel demand models consist of several components that work together, usually in a sequential manner, to produce the desired outputs and performance metrics for a scenario represented by a set of input data items. This is achieved through a set of various mathematical formulations related to the individual components. As noted above, there is uncertainty associated with the input data and with the parameters of the model components; additionally, it is recognized that errors in earlier model steps may propagate to produce larger errors in subsequent steps [32].

It is important for users of model results to recognize that a modeled scenario produces outputs that represent a **point forecast**, and error associated with the precise forecast may be difficult to quantify.

2.7.1 Ways of Dealing with Modeling Uncertainty

Because of the uncertainties and the assumptions involved in forecasting, it has long been recognized that model outputs used in planning analyses, such as forecasted link volumes, should not be treated as precise, accurate estimates of future traffic volumes. (Section 13.1 discusses in more detail the presentation of modeled link volumes.) However, it is impossible to quantify the error associated with particular model outputs, partly because the error in model inputs (such as socioeconomic forecasts) is unknown, and partly because the complexity of travel model structures does not lend itself to error computation.

Three methods for dealing with model uncertainty are discussed below: scenario analysis/ sensitivity testing, risk analysis, and exploratory modeling and analysis.

2.7.2 Scenario Analysis/Sensitivity Testing

A common method for considering uncertainty in model results is by running a variety of scenarios with varying model inputs (or parameters) and comparing the results of the different scenarios. This is a form of sensitivity testing, where the sensitivity of the model to various assumptions is evaluated. For example, forecasted employment in a particular subregion could be increased or decreased by 10 percent, and the changes in results are compared to the base scenario. This type of process provides not only a range of outcomes reflecting the uncertainty about the employment forecast, but also provides information about how sensitive the model results are to employment data inputs.

Scenario analysis can be used to get a handle on the uncertainty related to new mobility and technology such as TNCs and CAV. For example, some researchers have posited that effective roadway capacity will increase when all vehicles are autonomous and higher traffic densities can be achieved, but there is a range of assumed capacity increases among various sources. A planner using a model to analyze CAV-related scenarios could run several scenarios with different assumptions about capacity changes, perhaps using findings from various research efforts. A range or distribution of changes in various model results could be obtained from the set of tested scenarios.

The main issues with scenario testing are:

- The results of each scenario represent a specific point forecast, and the analyst must make assumptions about the likelihood of each point forecast since they may not have equal probabilities of occurring. For example, in the case of effective capacity increases from a scenario where all vehicles are CAVs, the analyst might test scenarios where the non-CAV capacity is increased by 50, 100, and 200 percent. The 50 percent increase scenario might be more likely than the 200 percent scenario, and the 100 percent scenario might be more likely than either of the others. The analyst must decide how to present the results; showing only a range between the 50 percent and 200 percent scenarios might be misleading.

- There is a practical limit on the number of scenarios that can be tested. Even if a reasonable range for a variable to be tested could be determined, the response of the model results to changes in the variable might be nonlinear, and likelihood of occurrence might be higher over some parts of the range. Getting a useful picture of the distribution of outcomes across the range of uncertainty might require a large number of scenarios to be tested. Furthermore, there are probably multiple variables whose values are uncertain, especially in cases of forecasts and new mobility options or which observed data are rare or nonexistent. A case where there are only three uncertainty variables to be tested, each of which requires five different values to obtain a reasonable distribution, would still require 125 scenarios to be run to cover the entire uncertainty space.

The main advantage of scenario testing is that it requires nothing more than running the travel model in a typical way (though perhaps many times). The level of effort to set up the scenario runs is low; the main work for the analyst is to define the scenarios that will adequately describe the uncertainty space and to evaluate the results of the scenario runs.

2.7.3 Risk Analysis

Formal quantitative risk analysis methods have been used in other fields but have not been used extensively yet in travel demand forecasting. Lewis (1995) promoted the application of risk analysis in transportation planning and provided examples related to cost estimation. Such methods can provide additional value to a point forecast (or set of point forecasts from a series of scenario model runs) for specific types of applications, particularly analyses of whether a given alternative is financially or technically feasible or meets some benefit threshold. In these applications, the uncertainties inherent in models—and therefore the forecasts derived from the application of models—can directly affect decisions of whether to implement an alternative [34].

A quantitative risk analysis process estimates the probability distributions of specific model outputs based on the probability distributions of the model's inputs and/or parameters. In such methods, the uncertainties associated with model inputs and parameters are expressed in terms of their probability distributions. These distributions can be estimated in some cases, for example, where the data sources have known probability distributions. In most cases, however, the probability distributions are not known and will have to be assumed by the planners and analysts.

The probability distributions of the model outputs can be estimated using Monte Carlo simulation, based on the probability distributions previously determined for the model inputs. This process would require multiple runs of the travel demand model, with the number of runs dependent on the number of input variables or parameters that the analyst wishes to consider the related uncertainties. Once these model runs have been completed, the probability distributions of the model outputs can be related to the inputs through the use of simple models (e.g., linear regression) and used to determine the probabilities that specific performance measures or objectives are met, based on the model outputs.

An example of the use of risk analysis with a travel demand model is the California High Speed Rail project [35]. Risk analysis methods were used to estimate the probabilities of ridership and revenue goals for the proposed rail service being met.

2.7.4 Exploratory Modeling and Analysis

An exploratory modeling and analysis methodology builds on the risk analysis process by explicitly treating the model as a set of assumptions and hypotheses (i.e., inputs and parameters) and exploring the results (model outputs). This differs from the conventional approach of treating the model as a predictive tool that is assumed to represent an accurate surrogate to reality [36]. The Federal Highway Administration is conducting a project to develop exploratory modeling and analysis methods and tools for use in travel demand modeling applications [37]. This project, which is set to be completed in 2021, has developed an open source tool, TMIP-EMAT, which facilitates the use of exploratory techniques with travel models.

The exploratory modeling process, as described by Milkovits et al. (2019) [37], explicitly includes risk analysis techniques. It includes the following steps:

- **Identify Risk Variables**. Various factors associated with uncertainty in models are identified and translated into a set of model variables. Sensitivity tests are performed to identify the final set of risk variables based on model sensitivity and the likelihood of variation in the risk variable.
- **Develop Risk Variable Ranges and Distributions**. The range and distribution of each risk variable are estimated, based on relevant research and professional judgment. The distribution for each variable is based on the level of uncertainty associated with the variable. For example, a relatively flat distribution might be used for variables with greater uncertainty, while peaked distributions would be used for variables with less uncertainty.
- **Implement Risk Analysis**. This is done by developing a collection of runs of the travel model, each varying the values of risk variables, with the value for each variable chosen based on its probability distribution. From the inputs and outputs of those runs, "meta-models" of important model outputs are developed. The meta-models are simpler models of the travel model itself; in TMIP-EMAT, these are linear regression models of the set of risk variables. Finally, Monte Carlo simulation is performed using the risk variable distributions along with the meta-models to simulate thousands of possible outcomes of the important model outputs, based on the uncertainty quantified in the previous steps.

TMIP-EMAT is designed to work with a variety of model types, including conventional four-step travel demand models and activity-based models. As this is written, testing has been underway for the past year. The finished version of TMIP-EMAT will be available as an open source download.

2.7.5 Conclusions

Many agencies in Virginia have experience with scenario testing using their models. While it is important to understand the limitations of scenario testing, as described earlier in this section, it is currently considered **acceptable practice** to use scenario testing to deal with uncertainty in models.

Since risk analysis and exploratory modeling techniques have not yet been used in Virginia model applications, it is premature to recommend their use at this time. VDOT and other agencies will continue to monitor the research into and applications of these techniques to see how they can be used more broadly in Virginia.

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CHAPTER 3. MODEL VALIDATION PROCESS

Travel models are used to produce information that is used in the transportation planning process. This information consists of aggregations of the results of travel-related decisions made by the thousands of people in the region being modeled. The models use mathematical relationships to produce this information from a set of known or assumed input data describing the transportation system, its users, and other factors that affect travel behavior. However, not only are some of the inputs unknown (particularly forecasted data), but the mathematical relationships in the models themselves are estimated since they represent simplifications of human behavior. Furthermore, many of the factors affecting travel behavior are unable to be observed or quantified, making their representation in models incomplete or absent.

Model validation is the process of checking the models to ensure that their results are reasonable and the mathematical formulations properly sensitive to the input data, in light of the uncertainties associated with the model. The validation process includes checking that the model produces reasonable results when it is applied for a scenario that can be observed and that the results remain reasonable when the inputs are revised to reflect changes in the transportation system or the population of users.

This chapter describes the process for validating travel demand models in Virginia. It draws on the definitive reference source for model validation in the U.S., the Federal Highway Administration (FHWA) *Travel Model Validation and Reasonableness Checking Manual, Second Edition*, [38] hereafter referred to as the "FHWA Validation Manual." For a more complete description of the process, the reader is encouraged to refer to the FHWA document.

3.1 Overview, Concepts, and Definitions

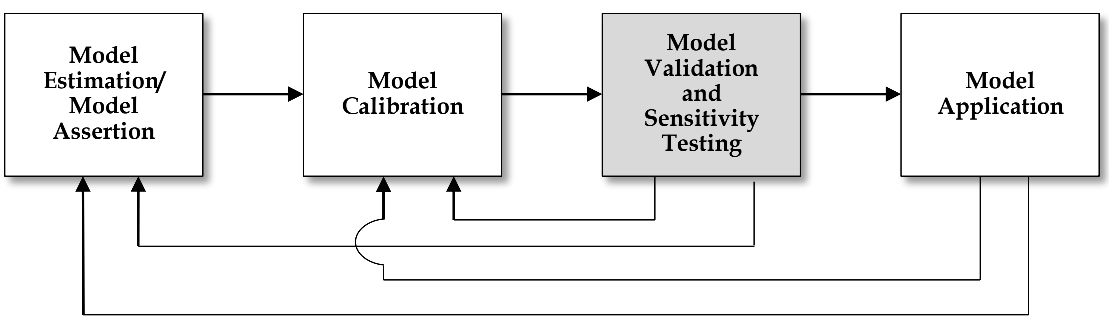
Since not all modelers and planners use the same terms to refer to components of the model development and application process, it is important to define the terms in a uniform way for use in this manual. Therefore, the terms are defined as in the FHWA Validation Manual. Some of the relevant terms as they are used in this manual are defined below.

- **Estimation** is the use of statistical analysis techniques and observed data to develop model parameters or coefficients. While model estimation typically occurs at a disaggregate level without bias or correction factors, model estimation also may use statistical analysis procedures to analyze more aggregate data.
- **Assertion** is the declaration of model forms or parameters without the use of statistical analysis of observed data. Model transfer from one region to another is a form of model assertion. The term "assertion" can apply to anything ranging from a single parameter to an entire model set.
- **Calibration** is the adjustment of constants and other model parameters in estimated or asserted models in an effort to make the models better replicate observed data for a base (calibration) year or otherwise produce more reasonable results.

- **Validation** is the application of the calibrated models and comparison of the results against observed data. Ideally, these observed data are not also used for the model estimation or calibration, but this is not always feasible in a practical setting. Validation data may include additional data collected for the same year as the estimation or calibration of the model or data collected for an alternative year. Validation also should include sensitivity testing, defined below.
- **Sensitivity testing** is the application of the models and the model set using alternative input data or assumptions. Sensitivity testing of individual model components may include the estimation of the elasticities and cross-elasticities of model coefficients. However, sensitivity testing also should include the application of the entire model set using alternative assumptions regarding the input demographic data, socioeconomic data, or transportation system to determine if the model results are plausible and reasonable.

The processes defined above, as they relate to the overall model development and application process, are illustrated in Figure 3-1. Model validation and sensitivity testing may reveal the need to return to the model estimation or model calibration steps. The application of the model using non-base-year conditions requires checking the reasonableness of projections and might also reveal a need to return to the model estimation or calibration steps. Issues uncovered during model application never lead directly back to the validation step since it is not possible to improve the model or model forecasts through additional validation. In some cases, however, additional model validation might be helpful in confirming the veracity of forecasts.

Figure 3.1 Model Development and Application Process



Source: Cambridge Systematics, Inc., "Travel Model Validation and Reasonableness Checking Manual," 1-5, Figure 1.1, 2010 [38].

3.2 Validation Process Description

3.2.1 General Concepts

The FHWA Validation Manual refers to five primary elements in the validation process:

1. Model validation plan specification;
2. Collection and assessment of validation data;
3. Validation of model components;
4. Validation of model system; and
5. Documentation of validation results.

Developing a model validation plan prior to beginning the validation (and preferably before beginning model estimation) is considered good practice. The development of a validation plan is not discussed in this manual; the reader is referred to the FHWA Validation Manual for information on this topic. The assembly of validation data (as well as other data needed for model development) is discussed in Chapter 4 of this manual. Documentation is discussed in Chapter 12. The remainder of this chapter, therefore, concentrates on Steps 3 and 4, the validation of model components and of the model system.

A critical concept of model validation is that <u>every component of a model must be validated</u> (Step 3), as well as the entire model system (Step 4). For the conventional four-step travel models used in Virginia, each of the four major components – trip generation, trip distribution, mode choice, and mode-specific trip assignment – along with the model input data and other components that might be part of the model system, such as vehicle availability or time-of-day modeling processes, must be validated individually. Since this manual has chapters referring to the major model components, the recommended validation tests that are specific to those components are described in the appropriate chapters.

Generally, it is good practice to perform the validation of the model components <u>as they are developed</u> (as opposed to long afterwards). For example, much of the validation of the trip distribution model can be performed immediately after model estimation (or assertion/ transfer), and the results can be compared to available data such as household travel survey information. However, it is necessary to recheck results for each component after the entire model development has been completed. This is especially important in models where any data are passed "backward," such as through logsums from subsequently applied components or feedback loops.

3.2.2 Accuracy Requirements and Guidelines

Accuracy requirements and guidelines for model validation depend on the intended use of the model being validated. Models used for project design or comparing alternative projects, especially for short-term planning, might require tight matches between modeled and observed travel data for model validation. In other cases, such as the evaluation of alternative transportation policies, the correct sensitivity of the model to the effects of the policies might outweigh the need for a close match of observed data. While the varying uses and requirements of forecasts could lead to the development of multiple models for a region, in Virginia it is common practice for agencies to develop a single model for an area and use it to provide forecasts for different types of analyses.

Reasonable validation guidelines may be important in helping establish the credibility of a model and helping model developers and users determine when the model is "close enough." The definition of acceptability guidelines needs to balance the resources and time available for model development with the decisions that will be supported by the travel forecast obtained using the model.

As in the FHWA Validation Manual, the term "guideline" rather than "standard" is used in this manual. The term standard connotes a formal definition of acceptance ("The standard has been met, therefore the model is valid," or, conversely, "the standard has not been met, and so the model is invalid"). The use of such rigid standards is not considered good practice and is not recommended in this manual. Simply matching model results within fixed percentages is insufficient to declare a model validated, and doing so ignores the differences in error ranges for models based on data from varying sources with different sample sizes, as well as the error inherent in the observed data sets themselves, which can vary substantially from one region to another.

Another reason that hard standards are not recommended is that revising the model during calibration in an attempt to meet a standard might make the model worse in other ways, such as diminishing its sensitivity to important variables. For example, one might introduce adjustment factors (known as "K-factors" in gravity model parlance) to attempt to get a better fit of district-to-district trips in a trip distribution model, but these factors might reduce the sensitivity of the distribution model to travel time because relatively large K-factors would become more significant than travel time and other variables in explaining destination choices. The large K-factors could also make it difficult for other model components to produce reasonable results.

The guidance in this manual therefore does not include requirements that any particular statistics must be within specific percentage ranges of the observed data. For the various model components, guidelines that are shown that can be considered useful targets, but they should not be considered pass/fail tests.

3.3 Static Validation for the Base Year

Comparisons of base-year model results to observations for a single "base year" are considered **static validation**. Ideally, the observed data sets used for comparison should not be the same data sets used for model estimation. Three typical examples are the following:

1. Traffic counts, which are not used in the development of highway assignment models, are commonly used as validation data for these models;
2. Transit rider surveys or rider counts can be used in the validation of mode choice and transit assignment models (although such data are sometimes used for mode choice model estimation); and
3. Observed speed data can be used to check reasonableness of estimated speeds by time of day for higher categories of facilities such as interstates, freeways, and major arterials.

In many practical settings, however, data sets other than the estimation data set are unavailable for the validation of some model components. This is especially true of model components for which travel behavior data – for which the main source is a household survey data set – is required for validation. There are seldom alternative sources for travel behavior information beyond the core survey. The National Household Travel Survey (NHTS) is available in all areas of the U.S., and the Commonwealth of Virginia invested in additional samples within the state, but the number of available household records is still limited when one considers the total number of households present in each region). Typically, sample sizes for household surveys are small enough that all of the data must be used for model estimation, and therefore the only data available for validation are the same data used in estimation. In these cases, it is good practice to make comparisons where possible to segments of the data not used for model estimation. For example, if the number of vehicles available is not a variable in the trip generation model, trip generation results can be compared for households with zero cars, one car, etc.

3.4 Dynamic Validation

Most travel models are based on "snapshot" data, such as household survey data collected over a relatively short period of time. The model relationships, parameters, and coefficients estimated from these data therefore reflect travel for the point in time represented by the model estimation data. However, the relationships may not hold true over time; the further one moves from the base year for validation, the more uncertain one should be regarding the appropriateness of the models. For this reason, good validation practice should include temporal validation for at least one year other than the base year for model estimation or calibration. The temporal validation should be performed for a year for which some validation data, such as traffic counts or transit boardings, are available.

This temporal validation, also known as **dynamic validation**, is an important aspect of model validation since it involves comparing model results to data not used in model estimation. Either backcasting or forecasting (or both) may be used for model validation. For example, if a model is estimated using 2020 survey data, the model could be used to backcast to 2010 conditions, and compared to year 2010 traffic counts, transit boardings, census data, or other historical data. Likewise, if a model is estimated or calibrated using 2015 survey data, a "forecast" validation could be performed against 2020 data.

Dynamic validation also includes **sensitivity testing**. Sensitivity testing can be performed by applying the model using alternative demographic, socioeconomic, transportation supply, or policy assumptions to determine the reasonableness of the resulting travel forecasts. The sensitivity of the model to the specific variable being varied can therefore be estimated by comparing the results of the alternative run to the base run.

The types of model inputs that might be varied during sensitivity testing could include the following:

- Land use/socioeconomic inputs – Examples (which may be regionwide or area-specific) might include increases in population or employment or changes in income levels;
- Highway Network – Examples might include travel times/speeds or auto operating costs; and
- Transit Network – Examples might include transit fares, headways, and operating speeds/times.

3.5 Model Calibration and Troubleshooting

When issues are found during the validation checks, due to significant differences between model results and observed data or to unacceptably high or low sensitivity to input variables, additional model calibration is needed. The appropriate calibration actions depend on the specific validation issues discovered. Generally, calibration consists of adjusting model constants and/or parameters to improve the model results, but other actions, including adding or removing explanatory variables, may be considered. It is also good practice to check the observed data being used for comparison and the model input data for errors that might be indicated by the validation tests. In the chapter for each model component, specific calibration or troubleshooting actions are presented for specific validation issues.

CHAPTER 4. DATA DEVELOPMENT FOR TRAVEL MODELING

This chapter describes the policies and procedures for developing data for models in Virginia. The data requirements include both what are needed as model inputs and data used for model development, estimation, and validation.

4.1 Travel Model Input Data

Data used as inputs to travel models include the following basic categories:

1. TAZ boundary information;
2. Land use/socioeconomic data, typically compiled at the TAZ level; and
3. Transportation networks, including a highway network for all models and a transit network for models where transit is modeled explicitly.

The sources and methods for compilation of these data categories are discussed in the remainder of this section. At the end of the sections on land use/socioeconomic data and transportation networks, a brief discussion of quality/validation checks of these data is provided. The quality of model results relies as much on high-quality input data as it does on well-calibrated model parameters. Reliable travel forecasts require reasonable future-year socioeconomic and network data forecasts. Thus, the success or failure of the modeling process rests on the input data. The old adage "garbage in, garbage out" is appropriate.

Many problems with model results are the result of errors in the input data. Before performing model development and application, a careful and comprehensive examination of all the data inputs to the travel demand forecasting process should be made and approved by the VDOT designated modelers. Additionally, consultants performing modeling work for VDOT may be asked to review or revise model input data if model results do not appear to be reasonable.

4.1.1 TAZ Structure

The following list summarizes recommendations on the best practices in delineating TAZs [39]. While it may not be possible to follow every one of these recommendations for every TAZ, the recommendations provide good guidance for model developers. These recommendations should be considered for both base-year and future-year conditions where feasible.

- The **model area** should be large enough so that most of the trips begin and end within the study area. The percentage of travel that occurs entirely inside a model area will vary depending on the size of the region, locations of political boundaries and geographic barriers (such as bodies of water), presence of major long distance highways (such as major Interstates), and the size and proximity of nearby areas that generate substantial travel. Ideally, 90 percent or more of all modeled trips would have both ends inside the region; however, in small areas, areas with major long distance highways, and areas near other large urban areas, this may not be possible.

- The TAZ structure should be **compatible with the base- and future-year highway and transit networks**. The level of detail in the highway network should be consistent with the TAZ structure (and vice versa) to permit proper network loading. For example, if the TAZ structure is too coarse relative to the highway network level of detail, many roadways could have modeled volumes of zero.
- TAZ boundaries **should be compatible with census, physical, political, and planning district/sector boundaries**. This will allow for compatibility with data sources (discussed further in the next section). The most recent U.S. Census geography should be followed. Preferably, TAZs should be block groups or combinations of block groups. In some instances, however, it is necessary to create TAZ geography at a sub-block group level. In these instances, TAZ boundaries must be combinations of census blocks. Areas with high employment, but relatively low population and fast growing suburban areas will most likely have block group sizes too large for TAZs.
- **Avoid concave borders** for TAZs. That is, avoid a TAZ shape whereby intrazonal travel could need to leave and reenter the same TAZ.
- TAZs should contain, as much as possible, **homogeneous land uses** in both the base and future year and should consider future significant developments. GIS can be a useful tool to check for homogeneity in population, employment, and other land use variables.
- The **average population per TAZ** should be between 1,200 and 3,000 for the base and future years. The population of most TAZs should fall within this range although there will be exceptions, such as in very sparsely populated parts of the model area or in locations with very high-density multifamily housing. This range provides a reasonable number of TAZs for computation purposes in most areas. In practice, this guideline works best for medium sized urban areas. For small urban areas, more TAZs are usually needed. For large urban areas this guideline is often not feasible computationally.
- Each TAZ should **generate less than 15,000 person trips** per day in the base and future year (trips produced in and/or attracted to the TAZ). Exceptions may occur for individual sites that generate very large numbers of trips.
- The **area of each TAZ** should be between 0.25 and 1.00 square miles. TAZs might be larger in more rural low-density parts of the model area and might be smaller in downtown areas with small blocks containing large buildings in large metropolitan areas.
- There should be a **reasonable (and relatively small) number of intrazonal trips** in each TAZ, based on the mix and density of the land use. (See Section 6.2, Trip Distribution Validation, for more information.)
- To the extent possible, **special generators and freight generators/attractors** should be isolated within their own TAZs.
- **TAZ numbering** should be sequential within jurisdictions, which is considered **<u>acceptable practice</u>**. Exceptions to sequential numbering, if necessary, should be

documented. It is **recommended practice** that all model regions adopt a numbering scheme for their TAZs that are sequentially nested within jurisdictions, with external stations being numbered at the end. Gaps should be left in the numbering between jurisdictions so that additional TAZs can be added without disrupting the overall numbering system. Table 4.1 shows an example of recommended and not acceptable TAZ numbering systems.

- **External zones** (also known as external stations) represent significant roadways that cross the model area boundary. Whether or not to include a roadway as an external station should depend on the roadway's regional significance and traffic volume. For a roadway to be regionally significant as an external station, its inclusion must have a significant impact on a model's forecast volumes over a substantial part of the model area. It is both **acceptable practice** and **recommended practice** for all model regions that external stations be regionally significant and have an annual average weekday daily traffic (AAWDT) volume of at least 500 for small urban areas and 1,000 for large urban areas.

The policies and procedures for practice in Virginia for definition of TAZs are summarized in Table 4.2.

Table 4.1 TAZ Numbering Recommended Versus Unacceptable Practice

Jurisdiction Number	TAZ Numbering	
	Recommended Practice	Unacceptable Practice
033	1-75	1-33, 111, 124, 167-179, 197, 318-326, 333, 411-412, 462-475
038	100-159	34-56, 104-110, 112-123, 180-196
043	200-254	57-93, 125-128, 327-332, 334, 346-351
046	300-402	94-96, 129, 211-224, 234-248, 267-279, 404-410, 413-461
051	450-535	99, 101, 197-210, 370-403, 467-501
Externals	575-598	465-466, 502-523

Table 4.2 TAZ Practice for Virginia Travel Demand Models

Component	Acceptable		Recommended	
	Small	Large	Small	Large
TAZ boundaries	Compatible with Census 2010/2020	Compatible with Census 2010/2020	Compatible with Census 2010/2020	Compatible with Census 2010/2020
TAZ numbering	Sequentially nested within jurisdiction to the greatest extent possible	Sequentially nested within jurisdiction to the greatest extent possible	Sequentially nested within jurisdiction	Sequentially nested within jurisdiction
TAZ population	N/A	N/A	One per 1,200 to 3,000 population	One per 1,200 to 3,000 population
TAZ trip generation	N/A	N/A	<15,000 Trips/ TAZ	<15,000 Trips/ TAZ
TAZ area	N/A	N/A	>0.25 to <1.00 square miles	>0.25 to <1.00 square miles
Inclusion of a roadway as an external station	Regionally significant and has an AAWDT of at least 500	Regionally significant and has an AAWDT of at least 1,000	Regionally significant and has an AAWDT of at least 500	Regionally significant and has an AAWDT of at least 1,000

4.1.2 Land Use/Socioeconomic Data

Local agencies are responsible for the base-year and forecast land use data necessary for travel demand forecasting. Population and employment estimates shall be based on official estimates of either the Weldon Cooper Center for Public Service of the University of Virginia, the United States Census Bureau, or other official government projections required for Federal transportation planning purposes.

A typical Virginia travel demand model input land use data file includes the following attributes: number of households, total population, population in households, population in group quarters, number of households, school enrollment by type of school (e.g., K-12 versus university), autos per household, and employment by type (e.g., retail and non-retail). These data are aggregated at TAZ level. Figure 4.1 shows land use file format used by Richmond/ Tri-Cities (RTC) model, Base 2017 [40]. The types of land use/socioeconomic data used in Virginia's travel models are discussed in the subsections that follow.

Figure 4.1 RTC Model Land Use Input Data Format, Base 2017

ZONE	PDC	JUR	JURNUM	JURCODE	TOT_POP	POP_HH	POP_GQ	HH	K12_ENROLL	U_ENROLL	AUTO	TOT_EMP	RET_EMP	NON_EMP	NAICS_11	NAICS_21	NAICS_22	NAICS_23
1	RRPDC	Richmond	1	127	10	10	0	4	0	0	0	66	0	66	0	0	0	18
2	RRPDC	Richmond	1	127	0	0	0	0	0	0	0	1074	35	1039	0	0	0	110
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1039	CraterPDC	Hopewell	9	116	182	182	0	62	0	0	88	836	34	802	0	0	0	9
1040	CraterPDC	Hopewell	9	116	269	269	0	89	0	0	127	97	35	62	0	0	0	0
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1163	CraterPDC	Petersburg	7	123	79	79	0	37	0	0	70	117	0	117	0	0	0	0
1164	CraterPDC	Petersburg	7	123	582	462	120	147	0	0	95	19	0	19	0	0	0	0
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1380	E	External	30		0	0	0	0	0	0	0	0	0	0	0	0	0	0
1381	E	External	30		0	0	0	0	0	0	0	0	0	0	0	0	0	0
1382	E	External	30		0	0	0	0	0	0	0	0	0	0	0	0	0	0
1383	E	External	30		0	0	0	0	0	0	0	0	0	0	0	0	0	0

Population and Household Data

This subsection addresses in turn four types of population and household data included in models and the common methods used to assemble them as inputs: total population and households for each TAZ, household size, automobile ownership, and cross-classification by multiple variables.

Total Population and Households for Each TAZ

Population is defined by the Code of Virginia in Section 15.2-4202:

> *"Unless a different census is clearly set forth, means the number of inhabitants according to the United States census latest preceding the time at which any provision dependent upon population is being applied, or the time as of which it is being construed, unless there is available an annual estimate of population prepared by the Weldon Cooper Center for Public Service of the University of Virginia, which has been filed with the Department of Housing and Community Development, in which event the estimate shall govern."*

The Weldon Cooper Center is the official agency of Commonwealth of Virginia for producing population annual estimates and projections. These estimates, including the official estimates of total population for localities, are used throughout the Commonwealth for decision-making and fund allocation. The population estimates are produced annually for each non-decennial-census year for each locality. When developing TAZ population and household data for travel demand model use, it is required that local agencies use the population estimates from Weldon Cooper Center as the control totals for each jurisdiction. For a model year in the past (e.g., developing a model with 2010 base year in 2013), the jurisdiction control totals should always be the same as the decennial census data (or Weldon Cooper annual estimates). The aggregate totals of TAZ population should be consistent with jurisdiction control totals. For future year population projections, it is allowed to have ±10 percent deviation from the projections Weldon Cooper Center published at the regional level. It is recommended that PDC/MPO/localities pre-coordinate with Weldon Cooper Center Demographics Research Group for any deviation that exceeds the indicated requirement.

Population totals for each TAZ should be segmented into population in households and population in group quarters, using the U.S. Census definitions. Population in group quarters includes residents of military barracks, college dormitories, prisons, long-term-care hospitals, boarding houses, and nursing homes. The decennial U.S. Census provides estimates for these segments; data from the Census Bureau's American Community Survey (ACS) may be used for years falling between decennial census years.

Further segmentation of population and household data is usually necessary. For trip production models (see Chapter 5, Trip Generation), households are often cross-classified by two variables, for example, number of persons by number of vehicles. Trip distribution and mode choice models are often applied to various segments defined by vehicle availability or income level. Acceptable and recommended practice for segmentation are discussed in later chapters on these model components.

Household Size

Trip production models, and sometimes other model components, often use as inputs the number of households segmented by the number of persons (household size) – for example 1-person, 2-person, 3-person, and 4+-person households. If the number of households in each household size category is not estimated directly (the Weldon Cooper Center produces estimates of population by jurisdiction, but not the number of households by household size category), then a segmentation procedure is used. For example, in the RTC Forecasting Model (Base 2017) [40], the following procedure was used:

1. Curves were estimated from data from the National Household Travel Survey (NHTS) to estimate the percentages of households of 1, 2, 3, and 4+ persons in a TAZ based on the average number of persons per household in the TAZ. Table 4.3 displays a portion of this table.
2. For each TAZ, the average household size is defined as the household population divided by the number of households. The number of households of 1, 2, 3, and 4+ persons in each TAZ is obtained by applying the corresponding percentages for the average household size, from the complete table (of which Table 4.3 is a part).

Table 4.3 Percent Household Distribution by Household Size

Household Size	1-person (%)	2-person (%)	3-person (%)	4+-person (%)
1.0	100.0	0.0	0.0	0.0
1.1	95.4	4.0	0.6	0.0
1.2	89.2	8.0	1.8	1.0
1.3	82.9	10.6	5.5	1.0
…	…	…	…	…
4.3	1.0	3.0	4.0	92.0
4.4	0.5	1.5	2.0	96.0

Source: Adapted from AECOM, "Richmond / Tri-Cities Model Update Technical Memorandum," 23, Table 4.2, 2020 [40].

Automobile Ownership

Many trip generation and mode choice models are applied to segments of households defined by automobile ownership, or vehicle availability, levels (for example, 0-vehicle, 1-vehicle, 2-vehicle, and 3+-vehicle households). There are various ways to estimate the number of households by number of vehicles. If estimates of the number of vehicles owned by TAZ are available (perhaps from motor vehicle registration or census data), an aggregate segmentation procedure similar to the procedure described above for household size segmentation can be employed. Another method is a disaggregate vehicle availability model, usually a logit model, that estimates the probabilities of a household owning zero, one, two, etc., vehicles based on demographic, location, and accessibility characteristics.

Cross-Classification by Multiple Variables

If a cross-classification of households is used as input into the trip production model and estimates of the percentage of households in segments or in cross-classification cells are not available, aggregate segmentation procedures are often employed. In the case of cross-classification, these may be two-step procedures where segments are defined for each variable (as described above for household size and automobile ownership) and the percentages in each cell estimated based on the marginal totals. For example, in the RTC model, Base 2017, after the households are segmented by number of persons and number of autos as described above, an iterative proportional fitting (IPF) [5] process is used to determine the cross-classification of households by persons and autos for each TAZ. For details of an IPF method, see [41]. The "seed" distribution for the IPF process was derived from NHTS data and is shown in Table 4.4 [40].

Table 4.4 Seed Table for Household Stratification in RTC Model, Base 2017

Persons/HH	Auto/HH			
	0	**1**	**2**	**3+**
1	0.056	0.217	0.034	0.014
2	0.015	0.053	0.153	0.100
3	0.002	0.027	0.064	0.075
4	0.011	0.006	0.078	0.094

Source: AECOM, "Richmond / Tri-Cities Model Update Technical Memorandum," 22, Table 4.1, 2020 [40].

Employment Data

Employment data should be classified in terms of a known industrial classification system. It is both **acceptable practice** and **recommended practice** for all model regions to use employment data and forecasts based on the North American Industry Classification System –

[5] The specific IPF process used is also sometimes referred to as the Fratar method.

United States (NAICS). The first two digits in the code are used to designate business sectors and are widely used in employment databases. The NAICS definitions for the various employment types, e.g., retail, nonretail, industrial, etc., should follow accepted practice for land use forecasting. In Virginia, MPOs and other agencies can obtain employment by county/ city from Virginia Employment Commission (VEC).

One of the best federal sources for at-work employment data is Quarterly Census of Employment and Wages (QCEW), also known as ES-202 data, which provides a quarterly count of employment and wages at the establishment level (company names are withheld due to confidentiality provisions), aggregated to the county level and higher (state, metropolitan statistical area). Data are classified using the NAICS.

The three widely used measures of annual county employment and wages by place of work are Bureau of Economic Analysis (BEA) employment data, the Bureau of Labor Statistics (BLS) employment data, and the Census Bureau's County Business Patterns (CBP) series employment data. BEA's estimates of total employment are derived from BLS data, which are the product of the Federal-State Covered Employment and Wages Program; data are derived from tabulations of monthly employment and quarterly total wages of workers covered by state unemployment insurance legislation and of Federal workers covered by unemployment compensation for Federal Employees (UCFE) program. BEA makes adjustments to account for employment not covered, or not fully covered, by the state unemployment insurance and the UCFE programs. BEA employment does not provide estimates for certain industries to avoid disclosure of confidential information, but the estimates for this item are included in the totals. These data are useful as comparisons or references at the jurisdictional level.

Longitudinal Employer–Household Dynamics (LEHD) is part of the Center for Economic Studies program within the U.S. Census Bureau that combines federal and state administrative data on employers (QCEW data) and employees (Unemployment Insurance earnings data) with core Census Bureau censuses and surveys, to create statistics on employment, earnings, job flows at detailed levels of geography and industry and for different demographic groups, and partially synthetic data on workers' residential patterns [42]. It has four statistical data products from the longitudinal data:

- The Quarterly Workforce Indicators (QWI) provide information about trends in employment, hiring, job creation and destruction, and earnings, with detail on geography, age, sex, and industry going as far back as 1990.
- The LEHD Origin-Destination Employment Statistics (LODES) provides annual employment statistics linking home and work locations at the census block-level.
- Job-to-Job Flows (J2J) provide access to worker flows between states, industries, and nonemployment.
- The Experimental release of Post-Secondary Employment Outcomes (PSEO) provides statistics on the earnings and employment outcomes of graduates of post-secondary institutions 1, 5 and 10 years after graduation.

The LODES dataset is state-based and organized into three types: Origin-Destination (OD), Residence Area Characteristics (RAC), and Workplace Area Characteristics (WAC), all at census block level. The WAC file provides information on the jobs located in each block, including the count of jobs in each of the 20 2-digit NAICS sectors, in each of three income categories, and by employee race, ethnicity, age, sex, and education level. This dataset is perhaps the most comprehensive and detailed publicly available data on the spatial location of employment throughout the country. The RAC file is the counterpart of the WAC at the residence place. The OD dataset provides information on commuting patterns and characteristics of both the workers and their jobs, including three industry categories, three income categories, and three worker age categories.

The LODES dataset is highlighted in OnTheMap, a mapping and reporting tool showing employment and home locations of workers with companion reports for user-defined areas [43]. It provides maps, charts, and reports on demographic characteristics and commute patterns of workers/jobs covering 50 states and District of Columbia. The QWI Explorer and J2J Explorer applications provide comprehensive data access and analytical capabilities through flexible charts, tables, and maps. PSEO Explorer is a light-weight interactive tool that enables comparisons of employment outcomes through dynamic grouped bar charts.

The limitations of the LODES should be noted: (1) it accounts for approximately 95 percent of wage and salary jobs and excludes self-employed individuals; (2) it does not include military and other security-related federal agencies, U.S. Postal Service workers, some employees at nonprofits and religious institutions, and informal workers; and (3) employment location is reported by employers, which may not be the location at which an employee performs his/her work duties in some cases. This is typical of those establishments with a headquarter location such as school districts, or certain types of jobs, such as home health aides, construction workers, and bus drivers, for which the work is mostly performed at a location physically separate from the office.

Commercial data sources for employment include market research listings and employment data providers. Many business research firms (e.g., Infogroup, Dun and Bradstreet, etc.) sell listings of all (or major) employers and number of employees by county and city. These listings show business locations by street addresses, as well as post office boxes. The Woods & Poole employment database includes full- and part-time jobs by major industry and by place of work, and includes historical data, for geographic areas (regions, states, counties, and Core Based Statistical Areas). Its MSA Profile has population projections and economic projections for all Core Based Statistical Areas (MSAs, CSAs, Micropolitan Statistical Areas, and Metropolitan Divisions) in the U.S., including annual projections to 2050 of population by age and race, employment by industry, earnings of employees by industry, Gross Domestic Product (GDP), personal income by source, households by income bracket, and retail sales by kind of business.

Employment data are the most difficult data component to collect. None of the data sources alone offers a complete inventory of employment by geographic location. Therefore, the methodology for developing the employment database should be based on the most efficient and accurate method by which employment can be collected and organized into the database file. All data must be related to specific physical locations by geocoding. Planning for supplementary local data collection remains the best option for addressing deficiencies in source data on employment; however, this effort must be planned several years in advance to ensure that resources can be made available for survey development, administration, and data analysis. For all sources of socioeconomic data, users must be aware of disclosure-avoidance techniques applied by the issuing agency and their potential impact on their use in model development.

Area Type

An area type classification scheme for TAZs can be used as a simplified mechanism to introduce additional information about land use into regional transportation models. Often, the area type classification is constructed to reflect information about land use development characteristics, including employment and population density.[6] Area type may be used as an input variable to models, e.g., trip generation and mode choice, and/or, can be used as an input in determining highway network attributes such as free-flow speeds and capacities. For use in determining network attributes, lookup tables are typically used to determine the specific input values, with area type often cross-classified with roadway facility type.

While it is **acceptable practice** for model regions not to use an area type classification scheme in their travel demand models, it is **recommended practice** that all model regions adopt an area type classification scheme system that contains at least three classifications: Central Business District (CBD), Suburban, and Rural. Large model regions should consider additional classifications. It should be noted that functions based on discrete area types can have the potential to introduce "cliffs" between otherwise similar TAZs that fall between two classifications (or sudden changes in roadway speeds or capacities as roadways pass from one area type to another).

As an example, the RTC model uses a set of five standard area type definitions: CBD, urban, dense suburban, suburban, and rural, described in Table 4.5 [40]. The area type on the network links is computed through an automated procedure described below:

1. Each link is assigned the TAZ number of the nearest TAZ.
2. A floating population and employment density is calculated for each TAZ by summing population and employment for all TAZs within one mile of the centroid and dividing it by the total area.
3. Stratification values for population and employment density are computed using the total mean and standard deviations (abbreviated "meanpop," "stdevpop," "meanemp," and "stdevemp."

   Population:
   - p1=mean pop – (mean pop / stdevpop)*0.5
   - p2=meanpop + (meanpop / stdevpop)*0

[6] In Virginia, some models use the term "LUD" for "Land Use Density" in referring to their specific area type classification scheme.

- p3=meanpop + (meanpop / stdevpop)*1
- …
- p7=meanpop + (meanpop / stdevpop)*5

Employment:

- e1=meanemp – (meanemp / stdevemp)*0.5
- e2=meanemp + (meanemp / stdevemp)*0
- e3=meanemp + (meanemp / stdevemp)*1
- …
- e7=meanemp + (meanemp / stdevemp)*5

4. A predefined "area type cross-classification" lookup table (shown in Table 4.6) is read with an area type value defined for each combination of the above population and employment stratification values.
5. Area type for the TAZ is defined based on its population and employment density using the above lookup table.

(Note: The above automated procedure does not define the CBD area type, which is defined manually by VDOT through an override attribute in the input network. The area types for freeways were also defined using the override attribute.)

Table 4.5 Example Area Type System for RTC Model, Base 2017

Area Type (LUD)	Description	General Parking Situation	Richmond Area Example
1	Central Business District (CBD) = Most Dense	Scarce and sometimes costly	Downtown Richmond and Petersburg
2	Urban	Limited	Fan and Church Hill
3	Exurban (Dense Suburban)	Adequate	Munford and Near West End
4	Suburban	Abundant	Glen Allen and Midlothian
5	Rural = Least Dense	Abundant	Goochland and Hanover counties

Table 4.6 Area Type (LUD) Lookup Table for RTC Model, Base 2017

Population Density Level	Employment Density Level						
	1	2	3	4	5	6	7
1	5	5	4	3	3	3	2
2	5	5	4	3	3	3	2
3	4	4	4	3	3	3	2
4	4	4	4	3	3	3	2
5	3	3	3	3	3	3	2
6	3	3	3	3	3	3	2
7	2	2	2	2	2	2	2

Summary of Procedures for Developing Socioeconomic Data

The policies and procedures for practice in Virginia for land use/socioeconomic data are summarized in Table 4.7.

Table 4.7 Land Use/Socioeconomic Data Practice for Virginia Travel Demand Models

Component	Acceptable		Recommended	
	Small	Large	Small	Large
Data sources	Estimates from local agencies, VEC, Weldon Cooper Center for Public Service of the University of Virginia	Estimates from local agencies, VEC, Weldon Cooper Center for Public Service of the University of Virginia	Estimates from VEC, Weldon Cooper Center for Public Service of the University of Virginia	Estimates from VEC, Weldon Cooper Center for Public Service of the University of Virginia
Employment classification system	NAICS	NAICS	NAICS	NAICS
Area type methodology	N/A	N/A	Yes, at least three classifications	Yes, at least five classifications

Note: The Bristol, Kingsport, and Washington, D.C. MPO (TPB) regions are exempt from this guideline.

Validation Checks for Socioeconomic Data

TMPD developed a series of checks for socioeconomic data for MPOs along several dimensions (jurisdiction, jurisdiction and TAZ, and TAZ) as part of the RTC model development effort. These checks are seen as useful to other MPOs or PDCs and are presented for reference in Figure 4.2.

Figure 4.2 Recommended Socioeconomic Data Checklist

Jurisdiction Level Checks

1. Population matches base year Weldon Cooper population control totals.
2. Population is consistent with Weldon Cooper population projections within established state guidelines.
3. Population/household ratio > 1.75.
4. Population/auto ratio > 0.75.

Jurisdiction and Transportation Analysis Zone (TAZ) Level Checks

1. Total population equals sum of population in households and group quarters population.
2. Total Employment equals sum of different employment categories.

Jurisdiction and Transportation Analysis Zone (TAZ) Level Checks

1. Total population equals sum of population in households and group quarters population.
2. Total Employment equals sum of different employment categories.

In addition to these rule-based checks, the FHWA Validation Manual provides details on other types of socioeconomic data checks that can be performed. These checks are summarized below.

The primary aggregate validation checks for socioeconomic data are the summation of TAZ data to different geographic areas and comparison to observed data. Summation of data such as population and households to political divisions such as cities and counties is particularly important. Comparison data is available from Weldon Cooper Center, decennial census, and the ACS. In addition to being able to check aggregate totals of data such as population and households, the ACS data provide the means to check information such as median incomes and income distributions, household size distributions, and vehicle availability distributions.

The ACS also provides a means to check employment data. The check will probably be most accurate at the regional level with decreasing levels of confidence for smaller geographic areas.

Multiple independent sources of disaggregate socioeconomic data are not generally available. Five-year ACS estimates of socioeconomic data are generally available for small-level geography. In Virginia, the Weldon Cooper Center provide estimates of socioeconomic data for years between census years through incremental annual updates to the most recent census data. The five-year ACS estimates of the socioeconomic data can thus be potentially used as independent estimates of the socioeconomic data on a TAZ-by-TAZ basis.

Disaggregate checks of employment data can be performed if independent data are available. For example, detailed checks of the input data might be made using files purchased from a commercial vendor.

On an aggregate level, regional rates can be calculated and compared to historical data for the modeled region. For example, trends in persons per household or vehicles per household could be examined. Reasonableness also can be checked using GIS plots of district-level or TAZ-level data, such as average household size, proportions of households by socioeconomic stratum (e.g., income level or automobile ownership), employment by category, and residential or employment density.

Sensitivity checks for socioeconomic data can be performed once the entire model is operational. These are done by adding or subtracting an appropriate type of activity (for example, number of households, retail employment) to a TAZ and evaluating the results for reasonableness. It would be expected that increases in activity would cause increases in the amount of travel (for example, traffic volumes), with larger increases nearer the TAZ where the amount of activity is increased, and decreases in activity would have the opposite effect. While it is impractical to do this for every TAZ, a small sample of TAZs, representing different types of development (commercial, residential, etc.), area types (urban, rural, etc.), and amount of activity, can be chosen.

4.1.3 Transportation Networks

Model networks have several components, including highway network links and nodes, TAZ centroids and centroid connectors, and, if transit is modeled, transit networks consisting of routes (lines) and stops. A centroid is a node that represents the center for activity for a TAZ and is the point from which trips to and from the TAZ are loaded during trip assignment. Centroid connectors are links that connect the centroids to the highway and transit networks and represent the local streets within a TAZ.

Transportation networks are important inputs to the travel demand forecasting process. Their development must be coordinated with MPOs/PDCs and their member jurisdictions, who are responsible for reviewing transportation networks for their areas and submitting written comments to VDOT listing recommended changes. VDOT’s Roadway Network System (RNS) is a good source for highway network data. Regional transit agencies, for example the Greater Richmond Transit Corporation (GRTC), should be contacted for transit network data.

When developing travel demand models in all regions, transportation networks must be created for the following scenarios:

1. Base Year; and
2. Constrained Long-Range Plan (CLRP).

Additionally, for model regions requiring air quality conformity analysis, additional interim transportation networks may be required. Networks for other scenarios, such as Vision Long-Range Plan (VLRP) and interim years other than those prepared for by air quality conformity, may be prepared but are not required.

Highway Networks

It is suggested that the VDOT Roadway Network System (RNS)/Linear Referencing System (LRS) roadway centerline and database system be used as a data source for highway networks. This system, which can be obtained from VDOT, provides the means of tracking and managing Virginia's road inventory and associated assets and attributes in a tabular, linear, and geospatial context. Using the RNS assures the accuracy of roadway representation and easier integration with other VDOT datasets.

Roadway Representation

The highway networks in travel models include a subset of all roads in the model region. Roads that carry small amounts of traffic or mainly local traffic are generally not included in the highway network. It is **acceptable practice** for all model regions to include major collectors and all higher functional classes in their transportation networks. Selected minor collector and local roads also may be included as needed to provide feasible paths between TAZs. It is **recommended practice** that all model regions include all nonlocal roadways, e.g., minor collectors and all higher functional classes, in their transportation networks. Selected local roadways also should be included as needed.

It is **acceptable practice** for all model regions to represent divided highways and their ramps and interchanges without roadway dualization (pairs of one-way links). It is, however, **recommended practice** that all model regions include roadway dualization in their networks to the greatest extent feasible. Dualization should generally be restricted to controlled access facilities such as freeways and major roadways with interchanges.

Centroid Connector Placement

For all model regions, GIS should be used to assist in the process of placing centroid and centroid connectors on the transportation network. Aerial photography and other land use GIS layers should be used as needed to identify logical access points for centroid connectors. While TAZs typically have at least two (and often more) centroid connectors to provide adequate access to the highway network, there are some situations where only one centroid connector is appropriate (for example, a development with only one entry/exit).

Highway Link Variables

It is **recommended practice** for all model regions to use the list of link variables shown in Table 4.8 for their next major model revision. Some commonsense rules for the values of link variables should be followed.

- If a variable is not applicable for a link or data are not available, a null value should be used, not a zero, since zero could be a valid value for the variable.
- Link attributes usually have specific formats as shown in the description and data type columns of Table 4.8.

Table 4.8 Recommended Link Attributes for Virginia Travel Demand Models

No.	Link Variable	Description	Type	Need
1	ANODE	Beginning node of model network link	Numeric	Model uses
2	BNODE	Ending node of model network link	Numeric	Model uses
3	DISTANCE	Highway Link distance in miles	Numeric	Model uses
4	LANES	Number of DIRECTIONAL through lanes	Numeric	Model uses
5	FACTYPE	Facility Type used for Modeling Only	Character	Model uses
6	TWLTL	Two Way Left Turn Lane	Character	Model uses
7	ONEWAY	Directionality Indicator	Numeric	Model uses
8	TRK_PHB	Truck Prohibition Identifier	Character	Model uses
9	POST_SPD	Posted Speed Limit in miles per hour (mph)	Numeric	Model uses
10	SPDCLASS	Speed class code from speed lookup table for the region	Numeric	Model uses
11	LINK_CAP	Link Capacity in vehicles/lane/hour if known	Numeric	Model uses
12	CAPCLASS	Capacity class code from capacity lookup table for the region	Numeric	Model uses
13	AAWDT	Annual average weekday count for Base Year	Numeric	Model uses
14	RTE_NAME	Local street name (911)	Character	Network Coding

Table 4.8 Recommended Link Attributes for Virginia Travel Demand Models (Continued)

No.	Link Variable	Description	Type	Need
15	RTE_NM	Route number	Character	Network Coding
16	PROJ_ID	Project ID used by VDOT and/or MPO	Character	Network Coding
17	YR_OPEN	Estimated year highway project open for traffic	Character	Network Coding
18	YR_CLOSE	Estimated year highway project closed to traffic	Character	Network Coding
19	JURIS_NO	VDOT's city/county jurisdiction code	Character	Reporting
20	FEDFUNC	Federal functional class	Character	Reporting
21	AREATYPE	Land use ID: Five types	Character	Reporting
22	FEDAT	Federal Area Type: Urban or Rural	Numeric	Reporting
23	MPO_ID	Identifier for which MPO region link belongs to.	Character	Reporting
24	SCRLN_ID	Screenline Identifier	Character	Reporting
25	CORD_ID	Cordon Line Identifier	Character	Reporting
26	CUTLN_ID	Cutline Identifier	Character	Reporting
27	TMS_ID	TMS Count Station ID	Character	State Database Connection
28	BEGIN_MP	Beginning Milepoint of a link	Numeric	State Database Connection
29	END_MP	Ending Milepoint of a link	Numeric	State Database Connection
30	HOVTYPE	HOV Type Identifier	Character	Model uses
31	TOLL_GRP	Toll Group	Numeric	Model uses
32	TOLLGATE	Toll Gate Group representing delay at toll barrier	Numeric	Model uses
33	R_AREATYPE	Area Type defined by User	Character	Network Coding
34	R_FFLOWSPEED	Free Flow Speed defined by User	Numeric	Network Coding
35	R_LINK_CAP	Link Capacity defined by User	Numeric	Network Coding

A data dictionary should be produced indicating the units or meanings of the values for all variables, especially those with "codes" (such as facility types or jurisdiction IDs). The values for the FACTYPE variable are shown in Table 4.9. Model developers should contact the VDOT designated modeler to obtain the values to use for these link attributes.

Table 4.9 Required FACTYPE Link Attribute Values for Virginia Travel Demand Models

FACTYPE	Brief Description	Additional Description	Example
1	Interstate/Principal Freeway	Controlled Access	• I-95, I-81, VA 76: Powhite Parkway (Richmond)
2	Minor Freeway	Controlled Access; Not necessarily built to Interstate standards	• Chippenham Parkway (Richmond) • U.S. 29 Bypass (Danville) • George Washington Parkway (NOVA)
3	Principal Arterial/ Highway	Limited Access, Multilane Divided	• U.S. 301 North of Bowling Green, U.S. 360
4	Major Arterial/ Highway	Highway with Posted Speed >50 mph or a Multilane Arterial	• U.S. 33, Monument Avenue (Richmond)
5	Minor Arterial/ Highway	Highway with Posted Speed <50 mph or a Single-Lane Arterial	• Huguenot Road Bridge, Three Chopt Road (Richmond)
6	Major Collector	Posted Speed >35 mph; Some through traffic	• VA 655: Beach Road Pump Road (Richmond)
7	Minor Collector	Posted Speed <35 mph; Little through traffic	• Most Smaller City/ Suburban/Rural Streets
8	Local	Only serves local traffic	• Local City/Subdivision Streets
9	High-Speed Ramp	Posted Speed >45 mph	• Interstate to Interstate Ramps
10	Low-Speed Ramp	Posted Speed <45 mph	• Most Interstate to Non-Interstate Ramps
11	Centroid Connector		
12	External Station Connector		

Some of the key variables are discussed in more detail below.

Link distances – For all model regions, it is **acceptable practice** to use existing "previously coded" distances in modeling. It is **recommended practice**, however, that all model regions use GIS tools to more accurately determine link distances.

Input Speeds – For all model regions, it is **acceptable practice** to use free-flow speeds as the basis for the input speeds used by the modeling process. Acceptable data sources for input speeds are speed limits (although they are generally lower than free-flow speeds for interstate and freeway facilities) and speed studies. It is **recommended practice** that all model regions use speed lookup tables as the basis for input speeds. An example of a speed lookup table is shown in Table 4.10.

Table 4.10 Example Lookup Table for Free-Flow Speeds (in mph)

	Area Type (Land Use Density) Category				
Facility Type	**CBD**	**Urban**	**Exurban**	**Suburban**	**Rural**
Interstate/Principal Freeway	55	58	62	65	68
Minor Freeways	50	55	58	60	62
Principal Arterial/Highway	25	28	35	43	50
Major Arterial/Highway	25	28	33	40	45
Minor Arterial/Highway	25	28	30	35	40
Major Collector	25	25	28	32	35
Minor Collector	25	25	28	30	30
Local	25	25	25	30	30
High-Speed Ramp	50	55	58	60	62
Low-Speed Ramp	20	20	25	25	25
Centroid Connectors	15	15	20	25	25
External Station Connector	25	25	25	25	25

Roadway Capacity – For all model regions, it is **acceptable practice** and **recommended practice** to use the most recent version Highway Capacity Manual (HCM) as the basis for roadway capacities. It is not acceptable to use older versions of the HCM or arbitrary figures for roadway capacities. Roadway capacities should be assigned to each facility type in the network using the established capacity lookup table for that particular region. It is both **acceptable practice** and **recommended practice** that all capacities represent Level of Service (LOS) E. An example of a fictitious capacity lookup table is shown in Table 4.11.

Table 4.11 Example Capacity Lookup Table (vehicles per lane per hour)

	Area Type (Land Use Density) Category				
Facility Type	**CBD**	**Urban**	**Exurban**	**Suburban**	**Rural**
Interstate/Principal Freeway	1,600	1,800	2,000	2,100	2,200
Minor Freeways	1,600	1,700	1,800	1,900	2,000
Principal Arterial/Highway	1,200	1,300	1,400	1,500	1,600
Major Arterial/Highway	1,100	1,150	1,200	1,300	1,400
Minor Arterial/Highway	1,000	1,050	1,100	1,150	1,200
Major Collector	800	850	900	950	1,000
Minor Collector	700	750	800	850	900
Local	600	650	700	750	800
High-Speed Ramp	1,600	1,700	1,800	1,900	2,000
Low-Speed Ramp	1,400	1,500	1,600	1,700	1,800
Centroid Connectors	10,000	10,000	10,000	10,000	10,000
External Station Connector	100,000	100,000	100,000	100,000	100,000

SCREEN_ID – The purpose of this variable is to serve as a flag for links that are part of a screenline, cutline, or cordon line. VDOT maintains a separate database file which lists the Link A and B nodes for all screenline, cutline, and cordon line links for every model region.

Additional link variables may be included as needed or desired. All additional link variables must be reviewed and approved by the appropriate VDOT designated modeler prior to being used in any model.

Turning Penalties

For small model regions, it is **acceptable practice** not to use turning penalties in the highway network. It is **recommended practice** for all model regions that turning penalties be included in the model as appropriate.

Summary of Highway Network Practice

Acceptable and recommended practice for highway networks is summarized in Table 4.12.

Table 4.12 Highway Network Practice for Virginia Travel Demand Models

	Acceptable		Recommended	
Component	**Small**	**Large**	**Small**	**Large**
Extent of roadway representation	Major Collector and above	Major Collector and above	Minor Collector and above	Minor Collector and above
Representation of ramps, roadway dualization, and interchanges	None	None	Yes	Yes
Centroid connector placement	Represent majority of traffic movement from each TAZ to adjacent network	Represent majority of traffic movement from each TAZ to adjacent network	Represent majority of traffic movement from each TAZ to adjacent network.	Represent majority of traffic movement from each TAZ to adjacent network.
Turning penalties	None	Where applicable	Where applicable	Where applicable
Link distances	N/A	N/A	State database	State database
Input speeds	Free-flow speed		Free-flow speed based on lookup table	
Roadway capacities	Current HCM LOS E based on lookup table		Current HCM LOS E based on lookup table	
Link variables	N/A	N/A	See network attribute list	See network attribute list

Transit Networks

The primary source for transit network data is route maps and schedules provided by the transit operators. This information may be used for both transit network coding and network validation. Transit schedules and route maps are typically used to develop route itineraries and headways input to the travel models. They also may be used to help develop relationships between bus speeds and roadway speeds for buses operating in mixed flow or transit travel times for transit vehicles operating on exclusive guideways.

Generally, the information needed for transit networks is organized by routes, or lines. Stop locations are explicitly coded although this may be somewhat loose in areas with "flag stop" operations. Route-level information includes the stop locations, headways (by time period if applicable), and travel-time information for routes that operate on exclusive rights-of-way. Stop locations should be matched to nodes in the highway network. Fare coding should accurately reflect the fare system, including fixed-fare operation, zone fares, origin-destination-specific fares (such as in the Washington Metropolitan Area Transit Authority (WMATA) rail system), and transfer fares.

The General Transit Feed Specification (GTFS), developed by Google, has been used to provide data for model transit networks [44]. GTFS provides a common format for public transportation schedules and associated geographic information. Currently in Virginia, Blacksburg Transit, Charlottesville Area Transit, and Hampton Roads Transit provide public information through GTFS, as well as WMATA, Arlington Transit, and Fairfax County in the metropolitan Washington region [45]. (It should be noted that other transit operators in Virginia, such as GRTC, provide trip planner services on their web sites using Google Maps.)

Representation of Transit Routes and Services

It is **acceptable practice** and **recommended practice** for small model regions not to have transit represented in their models through transit networks as long as transit use does not account for a significant amount of regional travel and analysis of transit-related projects and planning is not a required use of the model. For large model regions, where such transit analysis is necessary, it is both **acceptable practice** and **recommended practice** to include transit networks in their models.

Mode Definition

For large model regions, it is **acceptable practice** to include all major bus routes and intraregional fixed guideway, including commuter rail services. It is **recommended practice** to include additional modes, e.g., special bus, ferry, etc., if they are regionally significant, defined as meeting one of the following conditions:

- Comprises at least 1 percent of regional trips;
- Comprises at least 1 percent of home-based work trips;
- Comprises at least 10 percent of transit trips; or
- Accounts for at least 10,000 daily trips.

Travel Times and Speeds

For large model regions, it is both **acceptable practice** and **recommended practice** to estimate network travel speeds from operator schedules for fixed guideway facilities. For transit services that operate in mixed traffic (mainly buses, but in some cases trolleys and light rail), it is both **acceptable practice** and **recommended practice** to estimate network travel speeds based on the speeds from the highway network. This is usually done by creating lookup tables or other relationships (for example, linear or piecewise linear formulas) relating the transit speeds to the highway network speeds, based on observed transit speed data. The relationships may consider the type of transit service (local versus limited stop), highway type, and area type.

Representation of Walk and Drive Access to Transit

For large model regions, it is **acceptable practice** to use distinct transit access links to represent walk and auto access and egress between TAZ centroids and transit stops. Typically, rules are developed to determine which stops may be connected to each TAZ. It is **recommended practice** to determine access and egress times through the highway network. Auto access and egress times can be estimated through the highway paths between centroids and stop nodes. Walk access times can be estimated through the same process by getting the distance and assuming an average walk speed; however, caution must be used in places where walk paths do not necessarily follow the model highway network.

For large model regions, it is **acceptable practice** not to explicitly represent park-and-ride lots in the transportation network; however, it is **recommended practice** to explicitly represent those lots served by transit in the model. Major park-and-ride lots used by travelers may be included if they are regionally significant (for example, facilities used by commuters in northern Virginia near HOV facilities). Small park-and-ride lot facilities used exclusively for carpooling are generally not worth including in the modeling process. If park-and-ride trips are explicitly estimated in the mode choice model, they should comprise a separate trip table and be assigned to the highway and transit network.

Summary of Transit Network Practice

Acceptable and recommended practice for transit networks are summarized in Table 4.13.

Table 4.13 Transit Network Practice for Virginia Travel Demand Models

Component	Acceptable		Recommended	
	Small	Large	Small	Large
Representation in model	No	Yes	No	Yes
Modes included	N/A	All intraregional fixed guideway and major bus routes	N/A	All intraregional fixed guideway and major bus routes; other modes if regionally significant
Network travel speeds and times	N/A	• From schedule for fixed guideway • From highway network for modes in mixed traffic	N/A	• From schedule for fixed guideway • From highway network for modes in mixed traffic
Representation of walk and auto access/egress to transit	N/A	Access links	N/A	Use highway network to estimate access/egress times
Representation of park-and-ride lots	N/A	No	N/A	Yes, for facilities served by transit included in the model.

Validation Checks of Transportation Networks

Roadway and transit networks should be subjected to validation checks. The primary validation checks for input transportation network data are the aggregation of coded network data by various strata for comparison to independently summarized data for the same strata. For example, the coded lane-miles of roadway could be summed by facility type, by speed limit, or by geographic area and compared to similar summaries from available GIS data. Disaggregate transportation network checks may rely on spot checks of the data. A random sample of coded network links could be selected and certain characteristics verified using aerial photographs. Links may be checked for "exceptional" characteristics; for example, a color coded plot of all coded one-way links in the modeled region with directional arrows shown could be produced since there should be a limited number of one-way links in the region. It also is possible to perform checks comparing detailed coding to reasonable ranges. For example, coded link lengths can easily be compared to straight line distances calculated from the coordinates of end nodes of the links. Any links with differences outside of a reasonable tolerance accounting for curves could be flagged and checked for reasonableness.

On the transit side, matching of transit line coding and transit schedule information may be performed on a spot check basis. As noted above, GTFS data is available from many transit providers. It can be especially useful for checking base year networks through mapping comparisons. Although simplifications are often required to represent transit lines in models, being able to display the actual route information in a spatially accurate depiction, versus simply looking at printed timetables, can be invaluable in accomplishing coding checks.

It is worthwhile to build and check selected paths through the transportation network. For the roadway network, both shortest free-flow time paths and shortest distance paths can be built and checked for reasonableness by planners familiar with the area. Path checks also can be performed by adding or removing links to see whether the resulting revised paths are reasonable. Similarly, for the transit network, paths can be built and zone-to-zone travel times can be reviewed, especially for selected destinations. For example, zone-level plots of travel time to an important destination can be created and reviewed visually for reasonableness.

After the model development is complete, additional network checks can be performed by running the model. These checks may involve adding or deleting links or changing link attributes such as speed or capacity to verify whether the model results are reasonable. Similarly, transit network connections can be varied to see the impact on transit ridership.

4.2 Data for Model Development and Validation

The subsections that follow provide a discussion of different types of data used in model development and validation processes, including survey data, traffic counts, and transit ridership counts.

4.2.1 Survey Data

Survey data can be useful in the model development and validation processes. Surveys are a valuable source of information on how transportation system users in various markets of interest behave and make decisions. The data from surveys can be used to test different model forms, to estimate model parameters, and to check model results for reasonableness. The travel markets of interest, and the corresponding surveys, may include the following:

- Residents of the model region (household activity/travel survey);
- Transit users (transit rider/on-board survey);
- Travelers entering, leaving, or traveling through the region (external travel survey);
- Visitors to the region (visitor/hotel survey);
- Travelers to specific travel generators (special generator survey); and
- Trucks and commercial vehicles (commercial vehicle survey).

Model parameters are estimated from local or other data sources or are transferred from other sources. Local data sources can include the types of surveys listed above. The household travel survey is the main data source for estimating parameters for trip generation, trip distribution, and mode choice models as well as other components that may be included in the model such as time of day or vehicle availability models. Transit surveys may be used to estimate parameters for the mode choice model (along with household survey data) and for transit assignment. External survey data may be used for estimating external travel components; visitor survey data for visitor models; special generator survey data for estimating travel to and from generators such as airports; and truck/commercial vehicle survey for models of truck and commercial vehicle travel. Historically, there have been some challenges conducting external travel surveys, visitor/hotel surveys, special generator surveys, and commercial vehicle surveys. With the recent emergence and growth of Big Data such as location-based service data from mobile apps, the travel patterns for external travel, visitor/hotel travel, special generators, and commercial vehicle travel can be derived from passive mobile data sources. The applicability of these Big Data sources in addressing the needs of representing these special travel markets will be discussed in subsequent sections.

With the exception of the NHTS, which is discussed below, it is unusual to use survey data collected outside the model region directly to estimate parameters for the region. The model parameters from other regions, though, are sometimes transferred from other regions without new analysis of the survey data from those regions. In general, estimating model parameters using local survey data is preferred while transferring model parameters from another region is acceptable; however, caution needs to be exercised to consider the similarities and differences in terms of regional characteristics.

Whether or not the model parameters have been estimated from local data or have been transferred or asserted, local survey data can be useful in model validation. Model results can be compared to statistics compiled from the survey data. These types of tests are discussed in the sections of later chapters dealing with model validation.

Household Activity/Travel Survey

The household travel survey is an important data source for model development. The National Household Travel Survey (NHTS) is the primary source of the nation's information about travel by US residents. The inventory of travel behavior includes trips made by all modes of travel and for various purposes. The most current survey (2017 NHTS) is the eighth in this series of surveys. While most of the core of the NHTS remained unchanged from earlier surveys, the 2017 NHTS represents slight changes in survey methods and procedures such as the inclusion of rideshare and carshare questions and the removal of the safe routes to school question series. For more details of the changes, please refer to the Chapter 3 of *2017 NHTS User Guide*.

Virginia participated in the Add-On program to the 2007/8 NHTS and is again taking part in the next NHTS Add-On program. FHWA has undertaken the NextGen NHTS with two components: the survey core data (National and Add-On Samples) and passive (origin and destination) data, according to the TRB 2018 NHTS Workshop E-Circular 238, which will be reflected in the next NHTS data release.

It is **acceptable practice** for all model regions for model parameters to be asserted, and it is acceptable for regions not to have conducted a recent household activity/travel survey. This practice is considered acceptable in Virginia in part because of the expense of conducting such surveys and in part due to the presence of an alternative data source in the form of the NHTS "add-on" data for the State, which was collected as part of the NHTS. While the sample size of the NHTS add-on for each region is smaller than what would have been collected in a typical household survey, the sample size is substantially greater than what would have been available only from the "national sample" of the NHTS. It is also considered **acceptable practice** to use the NHTS add-on sample as the de facto household travel survey in a region in Virginia.

It is **recommended practice** for all model regions to conduct a household activity/travel survey about every 10 years, coinciding as closely as possible with the base year for a model update. Even though usable model parameters can be obtained through transferal or assertion, local survey data can be a unique and valuable resource in model validation.

The American Community Survey (ACS) is an ongoing survey by the U.S. Census Bureau to gather information previously contained only in the long form of the decennial census, such as ancestry, citizenship, educational attainment, income, language proficiency, migration, disability, employment, and housing characteristics. ACS is conducted every month, every year, with a sample of addresses (about 3.5 million annually) in the 50 states, District of Columbia, and Puerto Rico, and with questions about topics not on the Census, such as education, employment, internet access, and transportation. The ACS questions related to travel focus solely on commuting and do not ask about nonwork travel. Respondents answer questions about where they work, what time they leave home for work, the means of transportation used to get there, the number of workers riding in the car, truck, or van, and how long it takes to travel to work.

ACS data are a very important data source for socioeconomic variables at a Census geography, including the distribution of households by household sizes, by household income, and by vehicle availability. These data are often used to develop demographic models.

A special tabulation of the ACS data specifically designed for transportation professionals is the Census Transportation Planning Products (CTPP) [7]data. CTPP data are especially useful for understanding home-based work trips. CTPP includes tabulations of interest to the transportation community for workers by place of residence, place of work, and for flows between place of residence and place of work. CTPP are the only ACS tabulations that include flow information. Examples of special dimensions of tabulation include travel mode, travel time, and time of departure. The CTPP tabulations are organized into three parts:

- Part 1:Residence-based tabulations summarizing worker and household characteristics;
- Part 2: Workplace-based tabulations summarizing worker characteristics; and
- Part 3: Worker flows between home and work, including travel mode.

It is worthy noting the differences between the CTPP and LEHD LODES data discussed as part of employment data source (Section 4.1.2). The two data sets are based on two different data collection methods (sampling vs administrative records), have different coverage of workers (16 years and over for CTPP vs no age limit but some exclusions for LODES), use different definition of jobs and workplace locations, among others (see Table 4.14). The LEHD should not be viewed as an alternative to either household travel surveys (including the CTPP) or to employer-based surveys (such as the QCEW), but rather as a complement to both types of data. The LEHD database does not contain information about the work trip itself; there are no attributes describing the choice of mode, route, travel and departure times, or costs for the trip to work. As compared to the CTPP, the LODES provides information on workplace and commuting flows at a finer geography (down to the census block level), while the LODES provides less workplace characteristics than the CTPP. The CTPP only accounts for workers of age 16 and older, primary jobs, and institutionalized group quarters. The responded workplace locations may not be accurate because some jobs require workers to travel to multiple places (i.e. construction workers). Because it is based on sampling , the CTPP data do not include low-frequency OD pairs and have non-sampling error and sampling error. By contrast, the LEHD-OTM provides a nearly complete enumeration of flows between worker residences and workplaces, including flows between low frequency OD pairs. LEHD data should be used in conjunction with sample-based travel survey data, like the CTPP, to smooth out the geographic distribution of home-to-work trips, and to develop more complete areawide OD matrices for home-based work trips that could be used in travel modeling applications. Table 4.14 summarizes the comparison characteristics of CTPP, LODES and NHTS.

[7] The CTPP is a State DOT-funded, cooperative program that produces special tabulations of the American Community Survey (ACS) data that have enhanced value for transportation planning and model development. For more information, go to https://ctpp.transportation.org/

CTPP are most frequently used as an observed data source for comparison during model validation, but are sometimes used as a primary input in model development, particularly in small areas where local survey data are unavailable.

The most recent CTPP data (based on 2012-2016 ACS data) were released in 2019. It is expected that the next standard CTPP data release is to be based on the 2017-2021 ACS data. Currently, the Census Bureau is conducting cognitive tests for new survey questions regarding options such as ridesharing, and such information might be available in the upcoming ACS and CTPP data.

It is **recommended practice** to use the ACS and CTPP in the regional model development process, especially in developing demographic models of household size distribution, household income distribution, and vehicle availability distribution.

Table 4.14 Comparing Characteristics of CTPP, LODES and NHTS

Categories	CTPP (ACS)	LODES (LEHD)	NHTS
Data source	2012-2016 5-year CTPP was derived from 2012-2016 5-year estimates of American Community Survey (ACS)-Survey of 3.5 million addresses	Used LEHD dataset from administrative records.	Used customized survey to randomly survey households on travel behaviors.
Sample size	Roughly 15.6% of all U.S. households	Full enumeration of covered employment categories.	2017 NHTS surveyed roughly 129,700 households. Add-On Program allows agencies to purchase additional data.
Data coverage	Provides special tabulations for residence, workplace and flows between home and work for the whole U.S.	Provides origin-destination (OD), residence area characteristics (RAC), and workplace area characteristics (WAC) for most states.	Survey samples represent all areas within the U.S.
Geographic coverage	Excludes counties with less than 20,000 population	50 states and District of Columbia	50 states and District of Columbia
Update frequency	The next version of CTPP uses 2017-2021 ACS. Release roughly every five (5) years.	Available annually since year 2002 with the exceptions of some states.	Release roughly every 5-10 years.

Table 4.15 Comparing Characteristics of CTPP, LODES and NHTS (Continued)

Categories	CTPP (ACS)	LODES (LEHD)	NHTS
Employment included	Workers of 16 years and over including telework and non-institutional group quarters. Do not capture secondary job and excludes workers living in institutionalized group quarters.	Includes all ages of workers, about 95% of private sector wage and salary employment. Do not cover self-employment, military employment, U.S. Postal Service, and informal employment.	Includes civilian, non-institutionalized population of five year-and-older. Excludes institutionalized group quarters and any living quarters with 10 or more unrelated roommates.
Demographic and workplace information	Workplace location, commute mode, departure time, arrival time, travel time, sex, age, race, ethnicity, earnings, poverty status, occupation, industry, class of worker, hours worked each week, weeks worked, number of vehicles available, household size, number of workers in household.	Provides workplace characteristics (i.e. firm size, firm age, NAICS industry sector, work location) and worker characteristics (i.e. primary/secondary job, earnings, education, age, gender, ethnicity, house location).	For each worker, NHTS provides information on full/part-time, number of jobs, job types, workplace location, usual mode, distance, and arrival time to work, drive alone/carpool, and flexibility in work arrival time.
Smallest geographic unit	Transportation analysis zones (TAZs)	Census blocks	Latitude and longitude of trip ends (for Add-Ons only)
Geocoding	92% of worker records are successfully geocoded to place level. The leftover cases are allocated to a workplace location for geographies down to the place level.	Geocode using detailed addresses within the administrative records	Uses online interactive tool to real-time geocode during the interview process.

Source: Westat, "2017 NHTS Data User Guide," 2018; B. D. Spear, "Improving Employment Data for Transportation Planning NCHRP 08-36, Task 098," 2011. Seo, et al., "The CTPP Workplace Data for Transportation Planning: A Systematic Review," 2017. M. R. Graham, M. J. Kutzbach, and B. McKenzie, "Design Comparison of LODES and ACS Commuting Data Products," Center for Economic Studies, Vol. CES 14-38, 2014, https://www2.census.gov/ces/wp/2014/CES-WP-14-38.pdf, accessed June 20, 2020.

Transit Rider Survey

Transit rider surveys (sometimes referred to as "on-board surveys" although they need not be conducted on transit vehicles) are important data sources for model regions where transit usage is regionally significant. It is both **acceptable practice** and **recommended practice** for models where transit is not modeled explicitly not to have a local transit rider survey.

However, where transit is explicitly included in the model, it is both **acceptable practice** and **recommended practice** to conduct a transit rider survey every five years. The Federal Transit Administration recommends this practice and strongly encourages applicants for Section 5309 New Starts funding to have conducted such a survey within the last five years, especially in areas of high growth where travel patterns rapidly change.

External Travel Survey

In an external travel survey, drivers of vehicles on a roadway crossing the model region boundary are surveyed through vehicle intercept or mailout/mailback surveys, where the license plates are recorded to determine to whom to send the surveys. It is **acceptable practice** for all model regions not to have a current external travel survey, especially in regions where external and through travel do not constitute a significant portion of regional travel. It is **recommended practice** for large model regions to conduct an external travel survey about every 10 years, preferably in coordination with a model update (and other survey efforts such as household activity/travel surveys). External surveys should be conducted for external stations serving major roadways: interstates, freeways, and major arterials, with perhaps a small sample of lower volume external stations to provide data that can be used for all smaller external stations. For small model regions, while data from an external survey can be valuable since the proportion of travel that crosses the regional boundary is generally higher than in larger areas, conducting such a survey is not considered **recommended practice** because of the relatively high expense of conducting such surveys in smaller regions. If external travel surveys are unavailable or cost-prohibitive, it is **acceptable practice** to use Big Data such as passive mobile data to support development of the travel patterns for external travel.

Visitor Survey

It is **acceptable practice** for all model regions not to conduct a visitor travel survey. For model regions where visitors account for a significant portion of regional travel, it is **recommended practice** to conduct such a survey about every 10 years. Such regions may be characterized as having:

- At least one major international airport;
- At least one major tourist attraction that attracts over 100,000 visitors per year;
- A high percentage of the perceived tourist travel comes from outside the model region; and
- Significant year-round visitor travel.

For all other model regions, it is **recommended practice** not to conduct visitor surveys, due to their expense and the relatively low level of information that would be obtained relative to other types of data collection efforts. It is **acceptable practice** to use Big Data such as passive mobile data to support development of the travel patterns for visitor travel.

Special Generator Survey

Special generators are defined as locations that generate substantial numbers of travel activities which are not captured well in the standard trip generation, trip distribution, and mode choice models. Major airports are usually best modeled as special generators, as are major tourist attractions and some military facilities. University student travel can also be the subject of a special generator model.

Special generator surveys can be relatively expensive to conduct because they focus on a small segment of travelers and they may require special permission (for example, due to security considerations in airports or due to privacy concerns in privately owned attractions). It is therefore both **acceptable practice** and **recommended practice** for small model regions to not conduct any special generator surveys although if resources are available, such surveys can be very valuable. It is **acceptable practice** to use Big Data such as passive mobile data to support development of the travel patterns for special generators (see Section 4.2.2).

As part of the 2009 NHTS, VDOT commissioned a university student supplement survey. This survey was conducted among students at four major Virginia state universities under the reasoning that the random-digit dialing (RDD) method used by the main NHTS add-on undersampled these populations. These data are available for use in Virginia model development efforts.

Truck Survey

Because of the difficulty and high cost associated with conducting truck surveys, it is both **acceptable practice** and **recommended practice** not to conduct truck surveys in all model regions. Methods for developing truck and commercial vehicle model components that rely on other data sources are discussed in Chapter 8, Truck and Freight Modeling. It is **acceptable practice** to use Big Data such as passive mobile data to support development of the travel patterns for truck travel.

Summary of Survey Data Practice

Acceptable and recommended practice for travel surveys in Virginia models are summarized in Table 4.15.

Table 4.16 Survey Practice for Virginia Travel Demand Models

Component	Acceptable		Recommended	
	Small	Large	Small	Large
Household travel survey data	N/A	N/A	Yes, every 10 years	Yes, every 10 years
Transit on-board survey data	N/A	Yes, every 5 years	N/A	Yes, every 5 years

Component	Acceptable		Recommended	
	Small	Large	Small	Large
External origin-destination survey	N/A	N/A	N/A	Yes, every 10 years
Visitor survey	N/A	N/A	N/A	Yes, every 10 years if regionally significant
Special generator survey	N/A	N/A	On a limited basis as needed	On a limited basis as needed
Truck survey	N/A	N/A	N/A	N/A

Note: It is acceptable practice to use Big Data to support model developments related to external travel, visitor travel, and special generators.

4.2.2 "Big Data"

There are a number of ways to effectively utilize Big Data to support travel modeling, in terms of model development and validation, and for various standalone applications. There are also several sources of Big Data, each offering something different from others. The main sources of Big Data that are discussed here include the following:

- **Mobile Location Data**. Location-based services (LBS) data and call detail records (CDR) data both fall into this category because these data are collected from mobile devices that individuals carry with them. These data are typically marketed for use in generating origin-destination (O-D) trip tables, but they can be useful for any application that requires identification of trip ends. These data are typically not robust enough to decipher the trajectory of movement from origin to destination, at least not on a widespread basis.
- **Connected Car and GPS Tracking Data**. These data come from transponders inside personal automobiles and can be used to track the trajectories of trips from origin to destination. These types of data are used to develop speed estimates on major roadways and infer typical routes used between O-D pairs.
- **Truck GPS Data**. These data also come from transponders inside vehicles, but in this case, those vehicles are trucks. These data can be provided as O-D trip table form or can be provided as disaggregate vehicle traces.

In the following subsections, each of these data sources is described in detail and the appropriate use cases for each are identified.

Mobile Location Data

As noted above, both LBS and CDR data fall under the umbrella of mobile location data. In both types of data, collection occurs when the mobile device makes contact with a transmission center—a GPS satellite in the case of LBS data or cell phone tower in the case of CDR data. The prompt for such transmissions is also different in that an LBS data point is collected when an app on the device updates the device location while CDR data is collected when the device transmits or receives text or phone signal. In addition, the spatial resolution of LBS data is more precise since it is GPS-based whereas CDR data relies on triangulation based on cell phone towers. These data sources share one feature in that data is collected at irregular intervals that depend on the usage patterns of the device user. As such, the quality of the data collected varies from one device to another. Most data vendors are now providing LBS data, so the remainder of this section talks specifically about those data.

There are a number of ways that LBS data can be used in the model development and validation processes. The following are best practice uses of LBS data:

- **Special Generators** such as airports, major establishments, and major recreational sites. LBS serves as a cost-effective data source to support modeling special generators. It is **acceptable practice** to use LBS data to support development of the travel patterns for special generators. See Section 5.1.5 for further details.
- **Visitor Travel**. LBS also serves as a cost-effective data source to support modeling visitor travel. It is **acceptable practice** to use LBS data to support development of the travel patterns for visitor travel.
- **External Travel**. LBS also serves as a cost-effective data source to support modeling external travel. It is **acceptable practice** to use LBS data to support development of the travel patterns for external travel. See Chapter 7 for further details.
- **Model Calibration and Validation**. LBS serves as a secondary data source to support the validation of trip distribution and time-of-day models. See Section 6.2 for further details.
- **Seasonality and Day of Week**. Many LBS datasets can easily provide estimates of travel patterns for different days of week and seasons of the year, which are useful information for certain types of applications. Measuring differences in travel patterns for different seasons or across days of week can provide a benchmark from which to estimate differences in key metrics like vehicle-miles and vehicle-hours of travel. These data can also be used to support specialized models in areas with heavy seasonal tourism and weekend visitors.
- **Measuring Changes in Travel Patterns on Frequent Basis**. LBS data provide a lower cost option (than surveys) to updating one's understanding of travel patterns on a more frequent basis (e.g., every 2 to 3 years). Measuring change between LBS datasets from different years would offer the opportunity to update the travel patterns in the model more frequently. Types of measurements that could be made using LBS data include:

  - Trip rates by geography;
  - Temporal distribution of trips;
  - Trip lengths; and
  - Mix and share of trip purposes.

Data expansion is a critical component of using LBS data for any of these purposes and one that may not be present in all LBS datasets. Expansion processes ensure that the level and mix of travel in the data are accurate. Biases can exist in these datasets from zone to zone and across area types; so expanding the data so it is representative of the true population is necessary. This is typically accomplished using Census demographic information to expand home-based trips.

Many LBS datasets have additional details not noted above, and there are other use cases that may be considered for these data. At this time, it is not recommended to use LBS data for these other use cases due to questions about data quality, though this may change in the future. The use cases for which the use of LBS data is not recommended include the following:

- **Mode Share Data**. One key feature of LBS data is that it is mode-agnostic, meaning that they include trips made by all modes. Many LBS datasets now include travel mode characteristics of trips, which are inferred from proprietary heuristics that are difficult to verify. If mode information from LBS data is to be used, it is critical that mode characteristics from LBS data be vetted thoroughly against other data sources. Transit network service information and count information should be used to validate the reasonableness of these data. Sense checks provide an additional layer of vetting that should be used.
- **Detailed Trip Purpose**. Home and work locations are relatively straightforward for LBS data vendors to identify, and this allows for reliable estimates of home-based work, home-based other, and non-home-based trips from LBS data. However, many LBS datasets now include more detailed trip purpose information that is largely based on establishment category (e.g., a visit to a restaurant might be labeled as meal purpose). Such purpose level information may not align with the relative trip purpose information found in a local travel survey because a travel survey directly observes the respondent's stated trip purpose while purpose must be inferred from the LBS data. Systematic differences, thus, may exist and use of LBS trip purposes should be viewed from the lens of providing distinct purpose level information than what is typically obtained from a survey.
- **Model Estimation**. One of the key missing elements of most LBS datasets are the linkage between travel patterns and demographics, though some LBS datasets are beginning to add demographic information. Mode inference is also an area of weakness for these datasets due to the additional layer of inference required to identify mode of trips in the data. Based on the existing evidence, these contextual travel characteristics may not be robust enough to reliably produce the inter-relationships we expect between key variables in the data. As a result, we recommend that household travel survey datasets remain the key source of data for model estimation purposes.

With that being said, for simple models that do not have a mode choice component and have relatively simple household market segments, LBS data may be suitable.

Connected Car and GPS Tracking Data

GPS tracking data is fundamentally different from LBS data because the data is collected at frequent and regular intervals (e.g., every few seconds), which makes these data appropriate for tracking the route used for a trip. However, these data are generally collected by devices located in private vehicles, and so these data cannot measure travel by other modes like transit or bike. Some data vendors package GPS tracking data with LBS data to provide datasets with route level information on top of O-D pattern level data.

GPS data show considerable advantages in some use cases, while they have limitations similar to those for LBS in terms of some use cases where they are not recommended, as discussed above. The following describes key use cases that GPS data are well equipped to serve:

- **Select Link Analyses**. Because GPS tracking data provides routing information, these data can be used for select link analyses to find the origins and destinations of trips using a particular roadway in the network. Typically, this type of analysis is done by using a network assignment model to assign a trip table to the network first and then analyzing the O-D flows of volumes assigned to a particular link. These data obfuscate the need for modeling and provide a direct data source. However, sample sizes should be examined carefully. GPS tracking data may contain only five percent or less of all vehicle trips on the network; so it is important and may be necessary to use district level O-D patterns to analyze select link, especially for longer distance journeys.
- **Corridor and Subarea Analyses**. GPS tracking data can support corridor-level studies. The data can be used to develop O-D auto trip tables that might be adjusted using matrix adjustment techniques to better match traffic counts and to provide turning movements. This approach can generate O-D tables as inputs to a subarea model and may be preferred to generating O-D trip tables directly from subarea models.
- **External Travel**. Like LBS data, travel into and out of the region can be tracked with GPS tracking data. Like LBS data, GPS tracking data cannot necessarily replace counting stations at external stations, as these data will only provide a sample of trips.
- **Travel Time and Speed Data**. Several data vendors use this type of data to provide estimates of travel times and speeds on roadways by time of day and day of week. These data can be used in several ways:
  - Calibrate model speeds;
  - Initial skims to the travel model (in feedback loop process);
  - O-D reliability metrics;
  - Calibrate volume-delay function parameters (e.g., decomposing travel time into free flow and delay times); and

- o Identify free flow speeds.

Truck GPS Data

Truck GPS data is similar to GPS tracking data except that it is specific to commercial vehicles. These data have GPS spatial precision, and data is collected in frequent and regular intervals, which allows for both identification of trip ends and routing. Unlike LBS and connected car data, however, truck GPS data are often available at a disaggregate level allowing the user to have access to individual ping location data.

It is important to note that different sources of truck GPS data provide travel patterns for different types of trucks. For instance, ATRI data predominantly come from heavy trucks (FHWA classes 8 to 13 or combination units) while StreetLight and INRIX data offerings include medium trucks (FHWA classes 5 to 7) and light trucks.

There are a couple of main uses for these data:

- **Truck O-D Table Generation**. These data can be used to identify trip ends and compile results into an O-D trip table for trucks. Expansion of the data is critical and not straightforward. When paired with a model, expansion is often performed by a factor method or ODME process so that assigned truck volumes more closely resemble truck counts.
- **Model Development**. These data can also be used for truck model development. By utilizing land use and employment data by sector, trip generation and distribution models of truck trips can be related to the economic development indicators for a region. As is the case for above, expansion is critical and not straightforward without relating assignment results against truck counts.
- **Tour-based truck models**. In addition to typical trip-based models, these data can also be utilized to develop tour-based truck models since the data are typically acquired as disaggregate points that can be compiled into trip rosters and chained together to create truck tours. The processed data can then be used to determine the volume of trips from and to freight activity centers connecting several industries by time of day, key highway corridors and other travel metrics like travel times, distances and stop durations.
- **Truck Routing Analyses**. Like the connected car data, truck routing information is also typically available from these data that can be used for various analyses such as select link or to analyze route usage by vehicle class.

4.2.3 Traffic Counts

Traffic counts are primarily used for the validation of highway assignment. Count data are used in link-level comparisons of modeled and observed volumes, for comparisons of volumes for selected groups of links (such as screenlines and cutlines), and in comparisons of modeled and observed vehicle-miles traveled (VMT).

Virginia Traffic Count Data

VDOT's Traffic Monitoring System (TMS) is VDOT's official traffic count system, or system of record for summary traffic data, and should be used as the primary traffic count data source in all model regions for all model development and application. Requests for special counts for model development or application are discouraged and must have their need clearly documented to be considered for approval by the VDOT designated modeler. The VDOT Traffic Engineering Division would ultimately address requests for special counts.

VDOT conducts a regular program where traffic count data are gathered from sensors along streets and highways and other sources. From these data, estimates of the average number of vehicles that traveled each segment of road are calculated and VDOT periodically publishes these estimates. The publication, "Average Daily Traffic Volumes with Vehicle Classification Data on Interstate, Arterial, and Primary Routes," includes a list of each Interstate and Primary highway segment with the estimated Annual Average Daily Traffic (AADT) for that segment. AADT is the total annual traffic estimate divided by the number of days in the year. This publication also includes information such as the following:

- Estimates of the percentage of the AADT made up by six different vehicle types, ranging from cars to double trailer trucks;
- Estimated Annual Average Weekday Traffic (AAWDT), which is the number of vehicles estimated to have traveled the segment of highway during a 24 hour weekday averaged over the year;
- Peak hour and peak direction factors used by planners to formulate design criteria; and
- Quality of counts for AADT, AAWDT, classification data, and peak hour factor estimate, in terms of data sources ranging from "Complete Continuous Count Data" to unfactored raw count data.

In addition to the Primary and Interstate publication, more than two hundred publications are published periodically, one for each of the counties, cities, and towns across Virginia. These publications are titled "Daily Traffic Volumes Including Vehicle Classification Estimates," where available; Jurisdiction Report numbers 000 through 340." Also available are a number of reports summarizing average VMT in selected jurisdictions and other categories of highways.

Data from TMS are used by VDOT staff and also are incorporated in many applications (Statewide Planning System, DOT Dashboard, VDOT GIS Integrator, Pavement Management System, Pavement Material Scheduling System, Highway Safety Improvement Program, Safety Analyst, and the Roadway Network System (Highway Performance Monitoring System and Railroad Crossings). Traffic data from TMS are also used by other transportation agencies (local, regional, and federal), private vendors, and institutions of higher education. TMS publications are available via the external website: http://www.virginiadot.org/info/ct-trafficcounts.asp or by requesting the data through the Traffic Engineering Division.

Adjustments to Traffic Count Data

Adjusting raw count data for daily, weekly, and seasonal variation for the model base year is necessary to process count data for use in model validation. For all model regions, it is both **acceptable practice** and **recommended practice** to adjust any raw counts collected for model development and application for daily, weekly, and seasonal variation in accordance with acceptable VDOT TMS count practice.

Traffic Count Coverage

Having adequate count coverage is important for model validation. Modeling efforts should make extensive use of VDOT TMS and other available data sources and tools to maximize count coverage and quality. Noncentroid links are defined as links that are part of the model region transportation network that are not centroid connectors or external station links. It is **recommended practice** to have a count coverage of 20 percent of noncentroid links for small model regions and 10 percent for large model regions. It should be noted, however, that more important than the total number of counts is the distribution of counts among geographic subareas, facility types, volume levels, and individual roadways (i.e., having counts on several different roadways is superior to having multiple counts on the same roadway). As discussed below, adequate count coverage on screenlines and cutlines is also important.

Cordon Line, Screenline, and Cutline Count Coverage

It is valuable in model validation to examine the amount of traffic across various lines that cross several roads in the highway network.

- A cordon line is a line that encloses a subregion of the model, often a CBD, city, or major activity center. The trips crossing the cordon line therefore include all trips to and from the subregion although they also may include trips that pass through the subregion (these trips cross the cordon line twice). The number and locations of cordon lines will vary depending on the geography of the model region; for example, a multicity region may have cordon lines around each city or CBD.
- A screenline is a line that crosses the entire model region, effectively splitting the model region into two parts, meaning that a trip from one part of the region to the other must cross the screenline. Ideally, a screenline will have a minimal number of trips where a logical path would cross the screenline twice. Depending on the geography of the region, it is useful to have at least one north-south screenline and one east-west screenline. Geographic or other barriers to transportation, particularly if they have limited crossing opportunities, often make good screenlines, especially rivers.
- A cutline is a line that crosses part of the model region, meaning that it is possible to build paths from one side of the cutline to the other that go around the cutline. They are often used in locations where a logical screenline cannot be created due to geographic, network coverage, or data sufficiency reasons.

These types of analysis lines should usually intersect a minimum of three links or link-pairs representing separate roadway facilities, but typically they will intersect many more. They should not include external stations since base-year external trip estimates are based directly on the traffic counts that would be used for validation. It is likely that there will be some overlaps among the various analysis lines, but lines that overlap substantially with one another should be avoided.

It is **recommended practice** that small model regions include at least 10 percent of their noncentroid links in their cordon line, screenline, and cutline coverage. For large model regions, it is **recommended practice** that at least 5 percent of their noncentroid links be included in their coverage.

Systematic Count Program

Having a systematic count program for collecting and assembling the necessary count data for model development and validation is vital to the modeling process. For all model regions, it is both **acceptable practice** and **recommended practice** to have a database of count locations and data which is regularly maintained and reviewed during the model improvement process.

Summary of Traffic Count Practice

Acceptable and recommended practice for traffic counts in Virginia models are summarized in Table 4.16.

Table 4.17 Traffic Count Practice for Virginia Travel Demand Models

	Acceptable		Recommended	
Component	**Small**	**Large**	**Small**	**Large**
Primary count data source	VDOT TMS	VDOT TMS	VDOT TMS	VDOT TMS
Count adjustment (seasonal, day of week, etc.)	Yes	Yes	Yes	Yes
Traffic count coverage[a]	N/A	N/A	20% of Links	10% of Links
Cordon line, screenline, and cutline count coverage	N/A	N/A	10% of Links	5% of Links
Systematic count program	Yes	Yes	Yes	Yes

Note: [a] Counts coded on non-centroid links.

4.2.4 Traffic Speed

The availability of network-wide speed datasets is of particular importance for growing interest in speed validation of travel demand models. The traditional collection methods for speed data, e.g., spot speed survey, floating car survey, speed sensors, etc., require significant amounts of effort and cost, either in installing speed sensors or in conducting speed studies. These data collection methods are therefore appliable only for specific locations or road segments. In contrast, the commercial speed datasets, mostly created using the probe data technology, comprise large volumes of traffic data on region-wide road networks. These traffic probe data have been used in congestion detection and transportation performance assessment in recent years. With their extensive coverage, the probe data sources also allow for comprehensive analysis of speed and travel time on a regional highway network.

The National Performance Management Research Data Set (NPMRDS) is a monthly archive of average travel times, reported every 5 minutes when data is available, on the National Highway System. FHWA acquired the first NPMRDS in 2013 and the second (v2) NPMRDS in 2017 for use in its performance measures and management activities. Separate average travel times are included for "all traffic", freight and passenger travel, all based on vehicle probe-based data. This data set is also available to State Departments of Transportation and Metropolitan Planning Organizations and their contractors to use for their performance management activities.

The probe data technology is evolving rapidly, in data collection, data fusion, as well as data compilation and analysis. Several studies were conducted to evaluate the speed data provided by these products, including the evaluation of the INRIX data against the ground truth travel time data collected on approximately 92 miles of road segments within the four states of Maryland, Virginia, Delaware and New Jersey, for the I-95 Corridor Coalition; and a Florida Department of Transportation evaluation of three traffic probe datasets on four routes (an interstate freeway route and three routes on principal arterials) in Tallahassee, Florida. In the current NPMRDS program, evaluation of the probe data was conducted periodically for different locations and road types (such as freeway in Florida and arterials in Washington), using data based on ground truth and/or wifi sensors. The I-95 Corridor Coalition considers an average absolute speed error of 10 mph or less and average speed bias of $\pm$ 5 mph to be acceptable. These studies provided valuable insights on the quality and applicability of these products for speed validation of travel demand models, including the following:

- In general, the speed data from probe data sources are reliable for freeway facilities. The variation of the speed data increases with congestion.
- The probe speed data for non-freeway facilities show a high degree of variation, due to various interruptions of traffic on the facilities such as intersection signals, road signs, parking, pedestrian activity, etc.
- With large amount of data, the use of probe data sources involves certain amount of effort for data processing, including data cleaning/filtering, data aggregation and network conflation. The robustness of data compilation would have major impacts on the reliability of data for speed validation of travel demand models.
- The probe data technology is evolving rapidly. The quality of the data is expected to improve progressively with the advancement of the data collection and analysis technology.

In addition to the probe data mentioned above, there emerges crowd sourced data in recent years, including Google Application Programming Interface (API), Waze Transport Software Development Kit (SDK), and Uber Movement. These crowdsourced data provide considerably more temporal and areal coverage than conventional travel time data collection efforts, but the quality of data and the consistency between different sources can be difficult to verify. Although quality of travel time data from these crowdsourced data has been evaluated in some studies, there remain cautions in using these data for model validation.

To support regional model development, the speed data can be used either to examine the parameter values of the highway assignment model (e.g., free flow speeds, volume delay functions, etc.), or to validate the model estimated speeds and travel time for interstates and freeways, which will be discussed in detail in Section 10.5.

4.2.5 Transit Ridership Counts

Transit ridership counts are primarily used for the validation of transit assignment. Mode choice validation is closely related to transit assignment validation, and so transit ridership counts also are used in the validation of mode choice models, primarily to provide information that is used in estimating transit mode shares.

Ridership data are measures of "unlinked" transit trips as they count the number of times a transit vehicle is boarded. These are distinguished from "linked" trips, which are the outputs of mode choice models. A transit trip with transfers is considered one linked trip, but multiple unlinked trips.

The main source for transit ridership data is from transit operators. These are generally provided at the route (line) level. For longer transit routes, it may be useful to have ridership provided by route segment. It is desirable for high-volume stations/stops/route termini to have boarding counts at the stop level. If there are high-demand park-and-ride locations, information on the number of park-and-ride trips is useful.

For models with time-of-day components, ridership data by time period are needed to validate the mode choice and transit assignment results by time of day.

CHAPTER 5. TRIP GENERATION

Trip generation is the first step in the four-step modeling process. In this step, the number of trips of each type begin or end in each location is estimated. It is standard practice to aggregate trips to a specific unit of geography (e.g., a TAZ). The estimated numbers of trips will be in the unit of travel that is used by the model, which is usually one of the following:

- Vehicle trips;
- Person trips by motorized modes (auto and transit); or
- Person trips by all modes, including both motorized and nonmotorized (walking, bicycling) modes.

Trip generation models require explanatory variables that are related to trip-making behavior and functions that estimate the number of trips based on these explanatory variables. These functions are usually assumed to be linear equations (often expressed as cross-classification formulations), and the coefficients associated with these variables are commonly called trip rates. These functions should always estimate zero trips when the values of the explanatory variables are all zero.

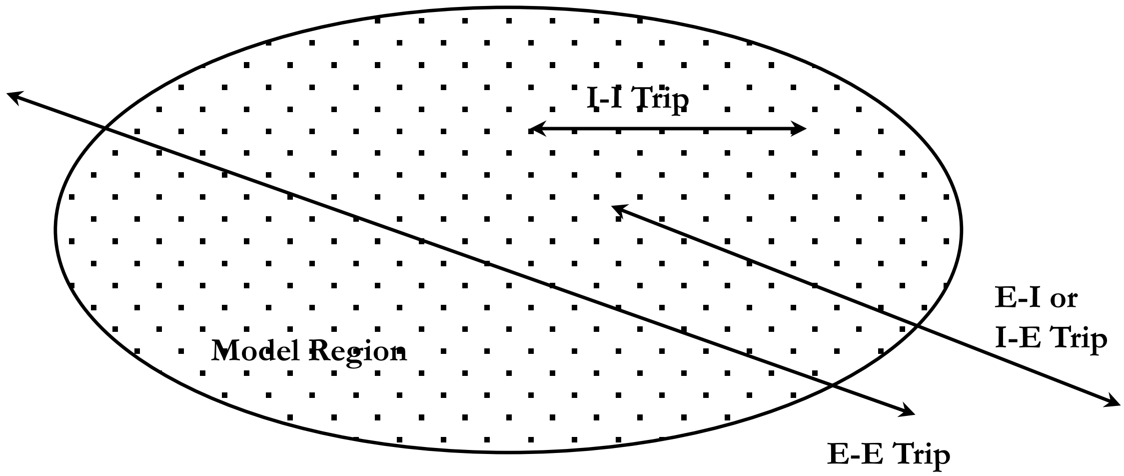
In four-step models, trip ends are classified as *productions* or *attractions*. The production end of a home-based trip is defined as the home end of the trip; the other end is the attraction end. There are advantages to the use of this convention in later model steps. For nonhome-based trips, the convention is to define the trip origin as the production end and the destination as the attraction end.

The inputs to trip generation models are socioeconomic and land use data, summarized at the TAZ unit of geography. The set of variables for trip production or attraction models depends on the trip purpose. For trip production models, the inputs are the number of households, classified by one to three variables that help explain trip making behavior. The input variables for trip attraction models are measures of TAZ activity such as employment by type, number of households or persons, and school enrollment.

The outputs of trip generation models are the number of trips produced in and attracted to each TAZ, by trip purpose. Sometimes trip outputs are segmented by a variable used in later model steps, such as income levels.

In most models, especially those for larger areas, the majority of trips are internal-internal (I-I) trips, which are both produced in and attracted to internal TAZs, that is, those TAZs within the modeling area. The trip generation process described in this chapter focuses mainly on these I-I trips; however, internal trip productions also include internal-external (I-E) trips, which are produced inside the model region (i.e., made by residents of the region) but are attracted to locations outside the region, and internal trip attractions also include external-internal (E-I) trips, which are produced outside the model region (i.e., made by nonresidents of the region) but are attracted to locations inside the region. Figure 5.1 depicts these types of trips. Chapter 7 discusses the modeling of external travel in greater detail.

Figure 5.1 Examples of Internal and External Trip Types



The remainder of this chapter describes the policies and procedures for developing, validating, and calibrating trip generation models in Virginia.

5.1 Trip Generation Practice

The policies and procedures for trip generation practice in Virginia are summarized in Table 5.1.

Table 5.1 Trip Generation Practice for Virginia Travel Demand Models

	Acceptable		Recommended[a]	
Component	**Small**	**Large**	**Small**	**Large**
Trip purposes (see text below for explanation of abbreviations)	HBW HBNW NHB	HBW HBNW NHB	HBW HBO NHB Others as appropriate (e.g., HBU)	HBW HBSc HBU HBSh HBO NHB Others as appropriate
Unit of travel	Vehicle trips	Person trips	Person trips	Person trips
Inclusion of nonmotorized modes	No	No	Yes, if nonmotorized travel is regionally significant	

Table 5.1 Trip Generation Practice for Virginia Travel Demand Models (Continued)

Component	Acceptable		Recommended[a]	
	Small	Large	Small	Large
Trip production model form	Cross classification or regression or logit model	Cross classification or logit model	Cross classification	Cross classification
Trip attraction model form	Regression	Regression	Regression	Regression
Sensitivity to land use/accessibility	No	No	Yes	Yes
Special generators	As needed		As needed	
Balancing trip productions and attractions	Home-based trip purposes balanced to productions and nonhome-based purposes to attractions		Home-based trip purposes balanced to productions and nonhome-based purposes to attractions	

Note: [a] Recommended characteristics are subject to resource constraints such as data availability and budget.

5.1.1 Trip Purposes

Travel behavior varies depending on the purpose of the activities being performed. Therefore, model accuracy is enhanced when trip purposes are distinguished in models. In conventional trip-based models, each stop to perform an activity constitutes the end of a trip. Typically, trips with one end at the traveler's home are distinguished from *nonhome-based* (NHB) trips, and sometimes trip purposes are further disaggregated among nonhome-based trips (for example, nonhome-based work and nonhome-based other). Nonhome based trips occur as part of trip chains or tours that generally begin and end at home.

Among home-based trips, *home-based work* (HBW) is always distinguished as a trip purpose since commuters to and from work exhibit different sensitivities to travel and environmental factors than travelers for nonwork purposes. *Home-based school* (HBSc) travel also is unique in terms of travel modes (since most students are too young to drive and some are so young that they require escorting), but data limitations sometimes prevent school travel from being modeled as a separate trip purpose. *Home-based university* (or college) (HBU) is another unique travel market, but usually it is only in areas with large colleges/universities that there is enough information to model such travel separately. *Home-based shopping* (HBSh) is another commonly modeled trip purpose. Other purposes such as *home-based social/recreation*, *home-based personal business*, and *home-based escorting* are sometimes used.

Unless there is an exhaustive set of home-based trip purposes, it is necessary to have a *home-based other* (HBO) trip purpose to account for home-based trip purposes that are not explicitly modeled. For example, if a model has HBW, HBSc, and HBSh purposes, there also will be a HBO purpose that would include trips made for other purposes such as personal business, recreation, etc. If a model has only a single home-based trip purpose other than HBW, this other purpose is usually referred to as *home-based nonwork* (HBNW).

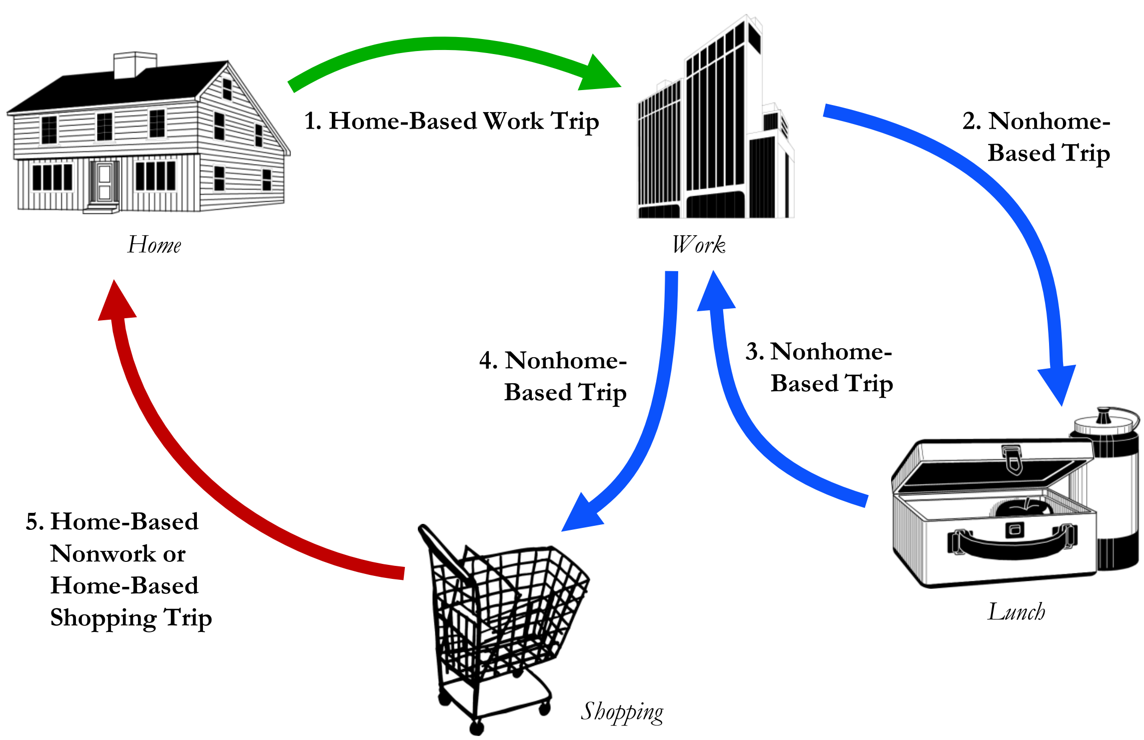
Figure 5.2 shows examples of the trip purpose definitions. From the definitions of production and attraction above, the production and attraction end of each trip is defined as follows:

- Trip 1 – Production is at home, attraction is at work;
- Trip 2 – Production is at work, attraction is at lunch;
- Trip 3 – Production is at lunch, attraction is at work;
- Trip 4 – Production is at work, attraction is at shopping; and
- Trip 5 – Production is at home, attraction is at shopping.

In the illustrated example, the production end is the origin for trips 1 through 4; it is the destination for trip 5. So, trip 1 is a HBW trip, but the journey home (trips 4 and 5) does not include a HBW trip because of the intermediate stop for shopping. Trip 5 is a HBSh trip. (Note that the trip purpose does not depend on which end of the trip is the origin—any trip where either end is at home is a home based trip.)

The example has three NHB trips. Trips 2 and 3 are part of a round trip made from the workplace. Trip 4 is part of the journey home from work, but since neither end is at home, it is a NHB trip.

Figure 5.2 Examples of Trip Purposes



It is **acceptable practice** for all areas to use three trip purposes: HBW, HBNW, and NHB. For smaller areas, it is **recommended practice** to consider the use of additional trip purposes, especially HBU if there is at least one major university in the region. For larger areas, it is **recommended practice** to consider the use of several home-based trip purposes as described above, depending on regional characteristics and data availability.

Note that truck and commercial vehicle travel is treated separately from the trip purposes for personal travel (although terms such as "truck trip generation" are used). Truck and commercial vehicle travel is discussed in Chapter 8.

5.1.2 Unit of Travel

As discussed in Section 2.2, the modeling approach may be a conventional four-step approach or a "three-step" approach, omitting the mode choice component. If a four-step approach is used, the unit of travel is the *person trip* so that travel by nonauto modes may be considered. In three-step models, the unit of travel may be either the *vehicle trip* or the *person trip*. It is **acceptable practice** for smaller areas to use the vehicle trip as the unit of travel; it is **acceptable practice** for larger areas to use the person trip. It is **recommended practice** for all areas to use the person trip as the unit of travel.

When person trips are modeled, they may include either only motorized trips or both motorized and nonmotorized trips. It is **acceptable practice** for all areas to model only motorized travel. It is **recommended practice** for all areas where nonmotorized travel is regionally significant to include both motorized and nonmotorized travel. Nonmotorized travel is defined as being regionally significant in urban areas if one of the following criteria is met:

- Urban area includes universities and colleges with combined student enrollment of over 20,000; and
- A grouping of at least 20 contiguous TAZs having the two highest area type classifications, CBD and Urban, exists in the model region.

5.1.3 Trip Production and Attraction Model Forms

Productions

The best practice for the form of the trip production model is considered to be a cross-classification model. The households in each TAZ are classified by two (occasionally three) variables that affect the amount of travel generated. The household variables used may include:

- Number of persons;
- Number of workers;
- Number of vehicles (autos);

- Number of children (for HBSc); and
- Income level.

(Methods for classifying households for model input are discussed in Section 4.1.2.)

The choice of variables depends on the significance in explaining travel by the trip purpose and the availability of data for model estimation and application. *NCHRP Report 716, Travel Demand Forecasting: Parameters and Techniques*, provides the following cross-classifications based on NHTS data:

- HBW – Workers by vehicles; persons by vehicles; persons by income level;
- HBSc – Persons by children; persons by vehicles; persons by income level;
- HBNW – Persons by workers; persons by vehicles; persons by income level; and
- NHB – Persons by workers; persons by vehicles; persons by income level.

The cross-classification table for each trip purpose provides the number of trips per household of each category. The values in each cell (sometimes called "trip rates") in the table may be estimated from local household surveys or transferred from a similar region or using national sources such as *NCHRP Report 716*. Table 5.2 presents an example of a cross-classification table for HBW productions from the RTC model, Base 2017 [40].

Table 5.2 HBW Trip Production Model from Richmond/Tri-Cities (Base 2017)

Number of Persons	Number of Vehicles			
	0	1	2	3+
1	0.264	0.682	1.375	1.628
2	0.55	0.682	1.375	1.639
3	1.10	1.320	2.002	2.739
4+	1.10	1.364	2.013	3.267

Source: Adapted from AECOM, "Richmond / Tri-Cities Model Update Technical Memorandum," 25, Table 4.4, 2020 [40].

The trip rates increase as the values of the input variables (persons and vehicles in the example in Table 5.2) increase. However, as is the case in Table 5.2, the rate of increase may not be linear. This nonlinear trend is one reason why cross-classification models are generally considered superior to linear regression models of trip productions. While regression is still considered **acceptable practice** for smaller regions for trip production models, cross-classification is considered **acceptable practice** for larger regions, and cross-classification is considered **recommended practice** for all regions.

It should be noted that NHB productions are estimated at the household level but represent trips that by definition do not begin or end at the home and therefore likely are generated in a TAZ other than the home TAZ. This issue is typically handled by using the cross-classification model to estimate total regional NHB productions and allocating the trips to origin TAZ using a function of TAZ activity (often the estimated NHB attractions).

In addition to the cross-classification model form, a multinomial logit (MNL) formulation is sometimes used to estimate trip productions for each trip purpose, where the alternatives are 0 trip, 1 trip, 2 trips, etc. The main advantage of an MNL formulation over a cross-classification model is the ability to use more variables to help explain trip generation. For example, the effects of continuous variables such as land use and accessibility, which are typically not included in the cross-classification formulation, can be tested as part of the logit model formulation. Therefore, the independent variables may include not only those that represent characteristics of a household, such as income level, number of vehicles, number of persons, and number of workers, but also characteristics of the area in which the traveler lives (for example, urban form variables that represent how densely developed it is, how diverse the land uses are, or whether it is in an urban, suburban, or rural area).

Attractions

Trip attraction models are estimated at a more aggregate level than trip production models, due to two main factors. First, survey data for model estimation are usually collected at the production end of home-based trip, i.e., the household. Second, the categorization of establishments is not as clear cut as it is for households since even within a particular classification (say, retail establishments), there are many potential subcategories. As a result, attraction models are often estimated from household survey data at an aggregate level such as districts.

The result of the necessary aggregation of data for model estimation is that the easiest type of attraction model to estimate is the linear regression model. Attraction models are therefore usually linear equations where the independent variables are employment by type and the number of households or population. For some trip purposes, other variables may be used – for example, school enrollment for HBSc trips.

The following are sample trip attraction equations from the RTC model, Base 2017 [40]:

- HBW attractions = 0.7007*Total Employment;
- HBSh attractions = 2.8248*Retail Employment + 0.3124*Households;
- HBO attractions = 0.8514*Total Employment + 0.8063*Population; and
- NHB attractions = 5.4285*Retail Employment + 0.6644*Nonretail Employment + 0.3311*Households.

Note that these rates are adjusted using both an area type factor and a zonal accessibility factor.

It is both **acceptable practice** and **recommended practice** for all areas to use linear regression as the form for trip attraction models.

5.1.4 Sensitivity to Land Use/Accessibility Variables

As described in Section 5.1.3, production and attraction models can include a variety of socioeconomic input variables. It is **acceptable practice** for all regions to include only these types of variables. However, it is **recommended practice** to consider including additional variables to reflect land use development or transportation accessibility characteristics. For example, the RTC model, Base 2017, uses an accessibility variable of the form:

$$A_i = \sum_j \frac{E_j}{t_{ij}^2} \quad (5\text{-}1)$$

Where:

A_i = Accessibility for TAZ *i*

E_j = Employment for TAZ *j*

T_{ij} = Travel time between TAZ *i* and TAZ *j*

A factor that is a function of this accessibility variable is used to adjust trip attraction totals.

5.1.5 Special Generators

There are often large activity centers in a model region that have unique characteristics that make it difficult for the trip generation models to accurately estimate the amount of travel. These locations, known as *special generators*, often include airports, military facilities, and large aggregations of certain activities such as regional medical facilities. (Major ports and intermodal facilities also fall into this category, but the additional travel activity is usually related to trucks rather than personal travel, and so they are discussed in Chapter 8 on truck and commercial vehicle modeling.) The number of productions and attractions for each special generator is estimated outside the trip generation models and is entered directly into model input files.

Because of their unique features, the only way to accurately estimate travel to and from special generators is through data collected specifically for these facilities, including special generator surveys (see Section 4.2.1), Big Data sources (see Section 4.2.2), and person and vehicle counts. It is recognized that it may be difficult to obtain data for some facilities due to security and privacy concerns. Therefore, it may be necessary to approximate the trips generated through counts on nearby roadways. It may be possible in some cases to transfer trip rates from estimates for other facilities inside or outside the region, but given the unique nature of each facility, this practice can result in substantial inaccuracy and should be only a last resort.

One key feature of LBS data is its GPS spatial precision. This allows for the estimation of trip ends in any geographic area, such as airports, establishments, or special generators such as stadiums. From this, it is possible to estimate key travel metrics associated with these locations, like trips generated, the distribution of travel patterns to/from these locations, and activity durations. In some cases, it may be necessary to refine the stopping criteria depending on the type of analysis. For instance, drop off trips at the airport are likely not to be considered stops by most LBS processing algorithms, but may be important for an analysis. In the past, it was typical to use surveys to collect information at these types of locations. LBS data can replace these types of surveys in many cases as long as detailed contextual trip information of travelers is not required.

LBS datasets inherently capture travel by anyone carrying a mobile device in a region, even travel by domestic visitors. As a result, LBS datasets are a rich source for visitor data. These data can be used to estimate the relative levels of trips generated by zone as well as the distribution patterns of visitor trips. Expansion is a critical element for visitor trips and can be very difficult, especially if the data is not expanded at the national level prior to the delivery to the client/analyst. Once the home information of the visitors is stripped away (as is often done when region cutouts of data are prepared), visitor expansion can probably only be accomplished via a single factor approach (e.g., multiply the visitor trip table by a single factor to inflate/deflate the entire trip table).

5.1.6 Balancing Trip Productions and Attractions

Because each trip has a production end and an attraction end, the number of regional productions should equal the number of regional attractions. (This equality is true for the sum of trips in all internal TAZs, meaning the sum of I-I, I-E, and E-I trips.) However, the sum of the modeled estimates of productions and attractions, which come from separate models based on different variables that are estimated from different sources, may not be equal. A process of "balancing" productions and attractions by trip purpose is undertaken to equalize the totals prior to trip distribution.

Since the TAZ productions for home-based trips are based on models estimated from survey data at the household level, and population and household data are generally of high-quality (from census data) compared to employment data, it is generally felt that home-based production estimates are more accurate than home-based attraction estimates. It is therefore both **acceptable practice** and **recommended practice** to balance regional trip attractions to equal productions for all home-based trip purposes. For NHB trips, as discussed in Section 5.1.3, the regional attractions may be balanced to match total regional productions, but the TAZ estimates of NHB trips are usually set to match the TAZ allocation of estimated NHB trip attractions.

5.2 Trip Generation Validation

5.2.1 Data Sources for Validation

The main validation checks for trip generation models involve comparisons of model parameters to trip rates from other regions and model results to observed trip making (based on survey data). The main data source for validation is therefore a household survey data set, if available. If establishment surveys are available, they may serve as validation data sources for trip attraction models.

When recent survey data that could be used for model estimation are not available, model parameters such as trip rates may be transferred from another model or from other data sources. A common source is the National Household Travel Survey (NHTS), described in Section 4.2.1. Some other national data sources include *NCHRP Report 716* and other documents (e.g., *TCRP Report 73, Characteristics of Urban Travel Demand*). These reports summarize information from the NHTS and from travel models for various types of urban areas and planning contexts.

5.2.2 Validation Checks

Table 5.3 summarizes the model validation checks for trip generation models.

Productions

The main checks of trip generation models are comparisons of aggregate model results, usually trips per household by purpose by various other market segments, to observed data from the local household survey (if available). Market segments may be defined by demographic or geographic characteristics, or any other variables by which model results and the comparison data sources are reported. The percentage of trips by trip purpose also may be checked for reasonableness.

Table 5.3 Trip Generation Validation Procedures for Virginia Travel Demand Models

Type of Check	Model Region Size	
	Small	**Large**
Compare trip production results to expanded survey data or NHTS	Reasonableness check only	Reasonableness check only
HBW attractions per employee	Reasonableness check only	Reasonableness check only
Unbalanced production/attraction ratio[a]	0.90-1.10	0.90-1.10
Area to area trip flows by jurisdiction	Reasonableness check only	Reasonableness check only

[a] Because of the interactions with the Washington metropolitan area, Fredericksburg may be considered an exception to this guideline.

If a model has been estimated using local household survey data, the model results can be compared to the results from the expanded household survey data. This is particularly useful if the comparisons are made using different stratifications of the data. For example, for a cross-classification trip production model using number of persons and income level, comparing the results of an application using the base-year socioeconomic data to the expanded survey results by area type could produce important insights regarding the validity of the model. Such a comparison could help identify errors in the model estimation and errors in the survey expansion (or differences to be checked between the household characteristics during the survey period compared to the model base year). However, problems with the survey data set itself, outside the expansion, might not be identified since they would exist in both the survey data and the models estimated from the data.

If a local household survey data set is not available, the best sources for checking trip production models are the national data sources. This is a good idea even if local survey data are available because the same data set will have been used for model estimation and validation. The most up to date summaries for the 2009 NHTS data can be found in *NCHRP Report 716* (in Tables C.5 through C.9 in that document) [3]. A summary of the information in these tables is provided in Table 5.4.

Another reasonableness check for cross-classification models is to ensure that the rates for individual cells are consistent with one another. This includes checking that the direction (increase/decrease) between trip rates in adjacent cells along both dimensions is correct. For example, for home-based work trips, the trip rate should be higher for a greater number of workers, holding the other variable constant. However, caution should be exercised since it may not always be correct that a higher value for a variable will result in an increase in the trip rate. As an example, a two person, one worker household might make more nonwork trips than a two person two worker household. The incremental differences between trip rates in adjacent cells also should be checked for reasonableness. For example, if household size is one of the variables, the increments between one and two person households, two and three person households, etc., should be reasonable in terms of the additional trips adding a household member would produce.

Table 5.4 Summary of Trip Production Information from 2009 NHTS

	HBW	HBNW	NHB	Total
Person Trips per Household (including nonmotorized)				
Population <500,000	1.4	5.1	3.0	9.5
Population >500,000	1.4	5.6	3.0	10.0
Percent of Person Trips per Household (including nonmotorized)				
Population <500,000	15%	54%	32%	100%
Population >500,000	14%	56%	30%	100%

Source: Adapted from Cambridge Systematics, Inc., et al., "Travel Demand Forecasting: Parameters and Techniques, NCHRP Report 716," c-13 to c-19, Tables C.5 through C.9, 2012 [3]

Attractions

The types of checks described above are relevant for trip productions since data sources such as the NHTS and local household activity/travel surveys use households as the sampling unit. There are few data sources for checks of trip attractions that collect information at the attraction ends of trips. *NCHRP Report 716* (Table 4.4 in that document, seen as Table 5.5

below) summarizes trip attraction model parameters from several urban areas around the U.S. While the attraction models summarized in that report vary widely in terms of the variable definitions and parameter values, the HBW models cited use total employment as the only input variable, with an average parameter of 1.2. The FHWA Validation Manual cites earlier sources that indicate a range of 1.2 to 1.6 for this parameter [38].

Table 5.5 Trip Attraction Rates from Selected MPOs (Person Trips per Unit)

	Number of MPO models Summarized	House-holds	School Enroll-ment [a]	Employment			
				Basic[b]	Retail [c]	Service [d]	Total
All Person Trips							
HBW	16						1.2
HBNW1	2	1.2	1.4	0.2	8.1	1.5	
HBNW2	8	2.4	1.1		7.7	0.7	
HBNW3	2	0.7		0.7	8.4	3.5	
NHB 1	5	0.6		0.5	4.7	1.4	
NHB 2	8	1.4			6.9	0.9	
Motorized Person Trips							
HBW	8						1.2
HBNW1	1	0.4	1.1	0.6	4.4	2.5	
HBNW3	4	1.0		0.3	5.9	2.3	
NHB1	6	0.6		0.7	2.6	1.0	

Source: Adapted from Cambridge Systematics, Inc., et al., "Travel Demand Forecasting: Parameters and Techniques, NCHRP Report 716," 42, Table 4.4, 2012 [3].

Note: [a] The number of elementary, high school, or college/university students in a zone.
[b] Employment primarily in two-digit North American Industry Classification System (NAICS) codes 1–42 and 48–51 [Standard Industrial Classification (SIC) codes 1–51].
[c] Employment primarily in two-digit NAICS codes 44–45 (SIC codes 52–59).
[d] Employment primarily in two-digit NAICS codes 52–92 (SIC codes 60–97).

Balancing Productions and Attractions

As discussed in Section 5.1.6, the estimated total trip productions and attractions are balanced for each trip purpose. The balancing process should not require major changes to the original model outputs. Therefore, prior to balancing, these totals should be compared by trip purpose.

Before checking the balance between productions and attractions, the effects of external travel must be considered. If significantly more people from outside the modeled region work, shop, and perform other activities within the region than residents perform these activities outside, there should be more internal attractions than productions, offset by a corresponding surplus of external trip productions over attractions. This imbalance must be carefully computed since many models use vehicle trips for external travel and person trips for residential travel. (External travel is discussed in Chapter 7.) The effects of special generators (see Section 5.1.5) also must be considered.

Once these effects have been considered, the balance between productions and attractions can be checked for each trip purpose. The ratio of regionwide productions to attractions by purpose should fall in the range of 0.90 to 1.10 prior to balancing. For the base year, the balance between productions and attractions is, in effect, a validation measure. If there is not a close match, the reasons for the lack of match should be investigated.

5.2.3 Model Calibration and Troubleshooting

Issues discovered during the model checks described above may imply errors in trip generation model parameters or input data (household and employment data at the TAZ level). Some of the typical problems that may be evident from these tests and possible calibration strategies are as follows:

- Total trips from base-year model results inconsistent with expanded survey data: Check survey expansion factors for consistency with model application data, check for differences in socioeconomic data between survey and base years, and/or recheck estimated model parameters.
- Trip rates inconsistent across variables in cross-classification model: Recheck inconsistent rates, check error levels for estimated rates, and/or "smooth" trip rates by combining cells in cross-classification.
- Model results inconsistent with national sources: Recheck estimated model parameters, check for ways in which local travel characteristics differ from national, and/or adjust parameters if they seem erroneous.
- Imbalance between modeled productions and attractions by trip purpose: Check consistency of survey data with model application data, or check to ensure that external and special generator trips have been correctly considered.

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CHAPTER 6. TRIP DISTRIBUTION

Trip distribution is the second step in the four-step modeling process. In this step, the number of trips generated in the trip generation step that travel between TAZs by purpose is estimated. These trips are in the same units used by the trip generation step (e.g., vehicle trips, person trips in motorized modes, or person trips by all modes, including both motorized and nonmotorized modes). Trip distribution requires explanatory variables which are related to the impedance (generally a function of travel time and/or cost) of travel between TAZs, as well as the amount of trip-making activity in the origin and destination TAZs.

The inputs to trip distribution models include the trip generation outputs – the productions and attractions by trip purpose for each TAZ – and measures of travel impedance between each pair of TAZs, obtained from the transportation networks. Socioeconomic and area characteristics are sometimes also used as inputs. The outputs are trip tables, production TAZ to attraction TAZ, for each trip purpose. Because trips of different purposes have different levels of sensitivity to travel time and cost, trip distribution is applied separately for each trip purpose, with different model parameters.

This chapter describes the policies and procedures for developing, validating, and calibrating trip distribution models in Virginia.

6.1 Trip Distribution Practice

The policies and procedures for trip distribution practice in Virginia are summarized in Table 6.1.

Table 6.1 Trip Distribution Practice for Virginia Travel Demand Models

Component	Acceptable		Recommended[a]	
	Small	Large	Small	Large
Model form	Gravity model	Gravity model	Gravity model	Destination choice model
Impedance measure	Highway travel time	Highway travel time	Highway travel time	Composite impedance that includes transit (if market is large) and any other significant modes
Income segmentation	No	No	No	Yes, for HBW
Singly versus doubly constrained	Singly or doubly constrained		HBW: Doubly or singly constrained. Other purposes: Singly constrained	

[a] Note: Recommended characteristics are subject to resource constraints such as data availability and budget.

6.1.1 Model Form

The **gravity model** is the most common type of trip distribution model used in four-step models. In Equation 6-1, the denominator is a summation which is needed to normalize the gravity distribution to one destination pair to those over all possible destinations. This is called a **doubly constrained** model since it requires that the output trip table be balanced to attractions, while the numerator already ensures that it is balanced to productions.

$$T_{ij}^{p} = P_{j}^{p} * \frac{A_{j}^{p} * f(t_{ij}) * K_{ij}}{\sum_{j' \in Zones} A_{j'}^{p} * f(t_{ij'}) * K_{ij'}} \quad (6\text{-}1)$$

where:

T^{p}_{ij} = Trips produced in TAZ *i* and attracted to TAZ *j*;

P^{p}_{i} = Production of trip ends for purpose *p* in TAZ *i;*

A^{p}_{j} = Attraction of trip ends for purpose *p* in TAZ *j*; and

$f(t_{ij})$ = Friction factor, a function of the travel impedance between TAZ *i* and TAZ *j*, often a specific function of impedance variables (represented compositely as t_{ij}) obtained from the model networks.

K_{ij} = Optional adjustment factor, or "K-factor," used to account for the effects of variables other than travel impedance on trip distribution.

Alternately, in a **destination choice** formulation, trip distribution can be treated as a multinomial logit choice model or similar formulation of the attraction location, in a manner consistent with the mode choice model formulation. In the logit model, the probability of choosing a particular alternative *i* is given by the following formula:

$$P_i = \frac{\exp(V_i)}{\sum_j \exp(V_j)} \quad (6\text{-}2)$$

where:

P_i = Probability of choosing alternative *i*

V_i = Utility (deterministic) of alternative *i*

The probabilistic nature of the choice reflects that the true nature of the complete utility function is unknown; the true utility includes variables not included in the deterministic component of utility V_i. The form of the utility functions is shown in Equation 6-3.

$$V_i = \sum_k B_{ik} x_k \quad (6\text{-}3)$$

where:

B_{ik} = The coefficient indicating the relative importance of variable *k* on choice *i*

x_k = The value of decision variable *k*

In such a formulation, the alternatives are the attraction TAZs, and the choice probabilities are applied to the trip productions for each TAZ. The utility functions include variables related to travel impedance and the number of attractions (the "size variable"), but other variables might include demographic or area type characteristics. A logit destination choice model is **singly constrained** since while the trip production totals are retained, the number of attractions is only an input variable, not a constraint or target. Sometimes, such a model is artificially constrained at the attraction end using TAZ-specific constants or post processing of model results.

While *best practice* for trip distribution models is considered to be a logit destination choice model, the gravity model is far more commonly used, primarily because the gravity model is far easier to estimate, with only one or two parameters in the friction factor formulas to calibrate (or none, in the case of factors fitted directly to observed trip length frequency distributions), and because of the ease of application and calibration using travel modeling software. Therefore, use of the gravity model for trip distribution is considered **acceptable practice** in all regions. In small regions, the gravity model for trip distribution also is considered **recommended practice**. In large regions, the destination choice model formulation is considered **recommended practice**.

6.1.2 Impedance Measure

One of the major inputs to trip distribution is the TAZ to TAZ travel impedance matrices. The term "impedance" refers to the generalized cost of travel between two TAZs. In most cases, the primary component of generalized cost is travel time, and so impedance is often expressed in time units such as minutes. The travel impedance variable may include several components. The simplest impedance variable is the highway (in-vehicle) travel time, which is an adequate measure in areas without a significant level of monetary auto operating cost beyond typical per mile costs – for example, relatively high parking costs or toll roads – or extensive transit service. In some areas, however, other components of travel impedance should be considered, creating a composite impedance measure. These may include distance, parking costs, tolls, and measures of the transit level of service. These measures, and the relative weights of each component, are often computed as part of utility functions in mode choice (see Chapter 9).

The individual components of travel impedance are computed as TAZ to TAZ matrices through "skimming" the highway and transit networks using modeling software. The components may be combined through a simple weighting procedure, which might be appropriate if all components are highway-related, or through the use of a logsum variable, which can combine highway and transit-related variables. In this case, the logsum represents the expected maximum utility of a set of mode choice alternatives and is computed as the logarithm of the denominator of the logit mode choice probability function.

It is considered *best practice* to use a composite impedance measure in areas with substantial transit use. Therefore, the use of highway travel time as the impedance measure for trip distribution is considered **acceptable practice** in all regions. In small regions, the use of highway travel time as the impedance measure also is considered **recommended practice**. In large regions, the use of a composite impedance measure is considered **recommended practice**.

6.1.3 Income/Vehicle Availability Segmentation

Besides segmentation by trip purpose, it is considered *best practice* to consider further segmentation of trip distribution using household characteristics such as vehicle availability or income level, at least for home-based work trips. This provides a better opportunity for the model to match observed travel patterns, especially for work trips. For example, if the home-based work trip distribution model is segmented by income level, work trips made by households of a particular income level can be distributed to destinations with jobs corresponding to that income level.

However, it may require substantial effort to segment attractions by income or vehicle availability level since the employment variables used in trip attraction models are not usually segmented by traveler household characteristics. Often, regional percentages of trips by income level, estimated from the trip production models, are used to segment attractions for every TAZ, especially for nonwork travel, but this method clearly is inaccurate where there are areas of lower and higher income residents within the region. *NCHRP Report 716* (see Section 4.5.2 of that report) has a discussion of segmentation processes and alternatives.

For Virginia models, it is considered **acceptable practice** in all regions to have nonsegmented trip distribution models. In small regions, the use of highway nonsegmented models also is considered **recommended practice**. In large regions, the use of trip distribution models segmented by income level for the home-based work trip purpose is considered **recommended practice**. At least three stratifications of income segmentation, if the observed dataset can support it, are recommended, with the thresholds for each range dependent on the income characteristics of the model region.

6.1.4 Singly versus Doubly Constrained Models

Most gravity models used in U.S. urban areas are doubly constrained. There is no consensus on *best practice* concerning whether it is always better to have a singly constrained or doubly constrained trip distribution model. For home-based work trips, some type of attraction end constraint or target seems desirable so that the number of work trip attractions is consistent with the number of people working in each TAZ. For discretionary travel, however, the number of trip attractions can vary significantly between two TAZs with similar amounts of activity, as measured by the trip attraction model variables. For example, two shopping centers with a similar number of retail employees could attract different numbers of trips, due to differences in accessibility, types of stores, etc. A doubly constrained model would have the same number of shopping attractions for both shopping centers, and a doubly constrained trip distribution model would attempt to match this number for both centers. So it might be reasonable to consider singly constrained models for discretionary (nonwork, nonschool) trip purposes although implied TAZ attraction totals from the outputs of such distribution models should be checked for reasonableness.

It is considered **acceptable practice** for all model regions to use either singly or doubly constrained trip distribution models. It is **recommended practice** for all model regions that the home-based work trip distribution model be doubly constrained while the models for other trip purposes be singly constrained.

6.2 Trip Distribution Validation

6.2.1 Data Sources for Validation

The main validation checks for trip distribution models involve comparisons of model results to observed travel patterns. The main data source for validation is therefore a household survey data set, if available.

For home-based work trips, an additional source is the Census Transportation Planning Products (CTPP), derived from the American Community Survey (ACS). It is important to note that work travel is treated differently in the ACS compared to travel models. The ACS asks about "typical" work travel behavior (where the person worked "most last week," how the person "usually" traveled to work, the "usual" departure time from home, etc.). The responses to these questions differ from the way that work travel is usually treated in household surveys and models, where travel to work on the specific travel day is considered. Furthermore, the ACS considers only travel to work, not from work. Additionally, stops on the way to and from work are ignored in the ACS, leading to a different definition of work travel from that of the home-based work trip in models. This implies that CTPP data, despite a larger sample size than household surveys, should be considered a secondary source for validation of home-based work trip distribution, compared to the primary source of household survey data.

LBS datasets can be a secondary source for validation of the trip distribution, as the travel patterns inferred from LBS data are more robust than a household travel survey. The LBS data can be processed to provide trip flows at the district level, intrazonal trips, and trip length distributions. However, overall trip distribution patterns should be checked and possibly adjusted as needed to ensure consistency with the assumptions in the model. One common feature of LBS datasets is that short duration stops and very short distance trips may be underrepresented slightly. Typically, these stops occur between two other anchor points (e.g., points A to B to C). Overall travel is not misrepresented, but this feature leads LBS datasets to have slightly fewer trips in total and slightly longer trip distances. Therefore, LBS data should be considered a secondary source for validation of trip distribution. When the primary source of household survey data has inadequate samples or is biased, it is acceptable to use the LBS data upon the consultation with the VDOT modeling staff.

6.2.2 Validation Checks

Table 6.2 summarizes the model validation checks for trip distribution models.

Table 6.2 Trip Distribution Validation Procedures for Virginia Travel Demand Models

Type of Check	Model Region Size	
	Small	Large
Intrazonal trips	Within three percentage points	Within three percentage points
Average trip length by purpose	Within five percent	Within five percent
Trip length (time and/or distance) frequency distribution – coincidence ratio	>0.70	>0.70
Area to area trip flows by jurisdiction	Reasonableness check only	Reasonableness check only

Note: Observed data from household survey or from CTPP for HBW trips.

Intrazonal Trips

Intrazonal trips are produced by and attracted to the same TAZ. Intrazonal trips are not assigned to the transportation network, and so having too many or too few intrazonal trips can result in a significant underestimate or overestimate of travel in a model region. The number of intrazonal trips depends on the TAZ size, but it is undesirable to have a large number of intrazonal trips so that the travel represented by the assignment process is as accurate as possible. However, it is impractical to model trip distribution at a level that includes very little intrazonal travel since the number of TAZs required would cause enormous model run times and file sizes.

The modeled percentage of regional trips that are intrazonal can be compared to the observed percentage, if observed data from household surveys – or from the CTPP in the case of home-based work trips – are available. The FHWA Validation Manual suggests that the modeled percentage for each trip purpose be within three percentage points of the observed value [38]. For example, if a trip purpose had an observed intrazonal trip percentage of 7 percent, the modeled percentage should be between 4 and 10 percent.

Average Trip Length by Purpose

Trip length by purpose, in terms of both time and distance, is one measure used in the validation of trip distribution models. Both the average trip lengths and the shapes of the trip length frequency distributions from the model are compared to observed data. Because of inaccuracies in reported travel times from surveys, observed trip lengths are computed using the time and distance skims from the model applied to the specific origins and destinations reported in the survey. Average trip lengths and trip length frequency distributions for the observed condition are computed directly from the trip table obtained from the expanded survey data and compared to trip table information obtained from applying the model.

Generally, the modeled average trip lengths for each trip purpose should be within 5 percent of observed. In models with many trip purposes, some purposes may have relatively few trips, and so the five percent guideline can be relaxed in these cases. It also is desirable to check trip lengths by market segment, with segments defined however possible given the model's capabilities and the information available from the observed survey data. For example, if trips by different income levels are modeled separately for a trip purpose, it would make sense to compare average trip lengths for each income level modeled.

NCHRP Report 716 reports average trip lengths in minutes from the NHTS for urban areas of different population levels. While these averages cannot be assumed to be representative of the average trip lengths in any particular model region, they may provide useful points of reference, particularly in areas without recent household travel survey data. The relevant averages for areas like those in Virginia are:

- Home-based work: Northern Virginia – 32, Hampton Roads/Richmond – 26, smaller areas – 21;
- Home-based school: Northern Virginia – 21, other areas – 18;
- Home-based other (nonschool): All areas – 18; and
- Nonhome-based: Northern Virginia – 20, other areas – 18.

Trip Length Frequency Distribution by Purpose

It is insufficient to check only the average trip lengths; the frequency distribution of trip lengths also must be checked. Visual checks can be very useful; the observed and modeled trip length frequency distributions can be plotted on the same graph to see how closely the distributions match.

A common way of checking trip length frequency distributions is through the use of coincidence ratios. This concept is most easily understood as the area under both curves divided by the area under at least one of the curves, when the observed and modeled trip length frequency distributions are plotted. Mathematically, the sum of the lower value of the two distributions at each increment of time or distance is divided by the sum of the higher value of the two distributions at each increment. Generally, the coincidence ratio measures the percent of area that "coincides" for the two curves. The coincidence ratio lies between 0 and 1.0, where a ratio of 1.0 indicates identical distributions.

The calculation of the coincidence ratio is defined in Equations 6-4 through 6-6.

$$\text{Coincidence} = \sum_{t=1}^{T} \min\left\{ \frac{f^m(t)}{F^m}, \frac{f^o(t)}{F^o} \right\} \qquad (6\text{-}4)$$

$$\text{Total} = \sum_{t=1}^{T} \max\left\{\frac{f^m(t)}{F^m}, \frac{f^o(t)}{F^o}\right\} \tag{6-5}$$

$$\text{Coincidence Ratio} = \frac{Coincidence}{Total} \tag{6-6}$$

where:

$f^m(t)$ = frequency of trips at time *t* from the model;

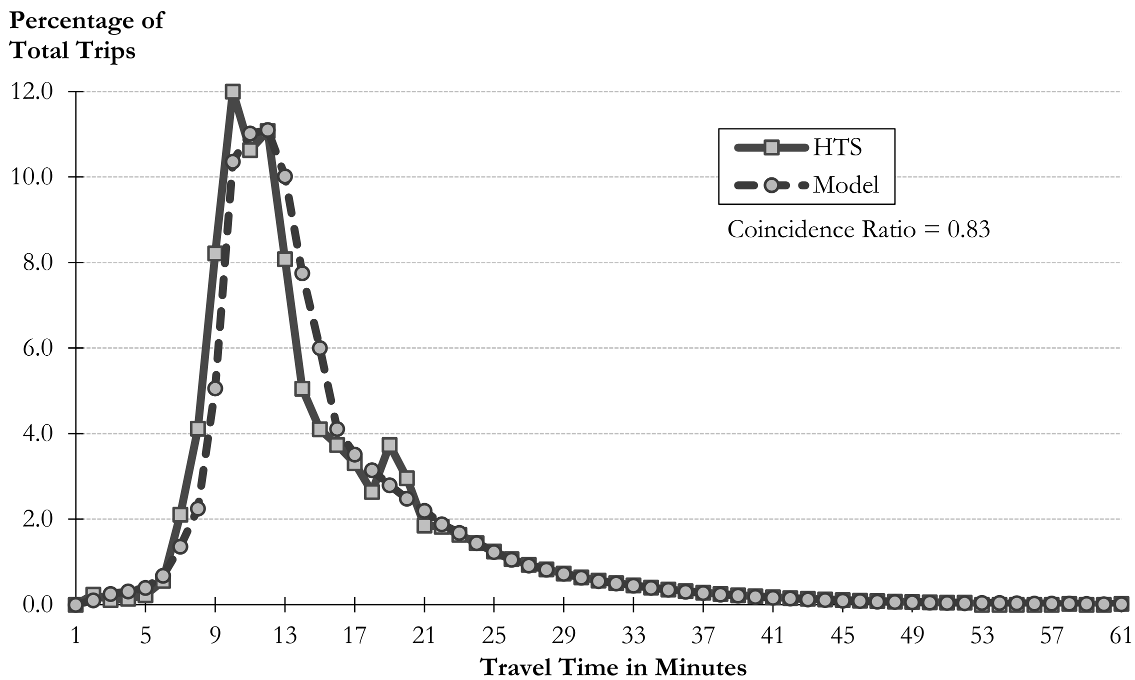
$f^o(t)$ = frequency of trips at time *t* from the observed survey data;

F^m = total trips distributed from the model; and

F^o = total trips distributed from the observed survey data.

Figure 6.1 shows an example of a coincidence ratio computation. It is preferable for the coincidence ratio for each trip purpose to be at least 70 percent. The 70 percent guideline can be relaxed in models with many trip purposes since some purposes may have relatively few trips, making a stronger statistical fit more difficult to achieve.

Figure 6.1 Example of a Home-Based Work Trip Length Frequency Distribution Comparison



Area to Area Flows of Trips by District

It is important to understand that matching average observed trip lengths or even complete trip length frequency distributions is insufficient to deem a trip distribution model validated. The modeled **orientation** of trips must be correct, not just the trip lengths. Because of sample size limitations of household surveys, it is necessary to check origin-destination patterns at an aggregate level. Generally, this is described as a **district-level** validation. The ideal number of districts is dependent on many factors, including the size of the modeled region, the number of TAZs, the amount of travel, the existence of political boundaries and travel barriers such as rivers, and the amount of market segmentation for which district-level analysis will be performed. As with other checks, district-level geographic checks should be performed separately for each trip or activity purpose. Additional market segmentation, such as by income level, also should be performed where the observed data exist and the model supports such segmentation.

District-to-district travel comparisons are reasonableness checks, and there are no specific guidelines for what constitutes a satisfactory match between modeled and observed data. This is because there is wide variation among models in terms of district definition and size, survey data sample sizes, and the number of trips by purpose.

6.2.3 Model Calibration and Troubleshooting

Issues discovered during the model checks described above may imply errors in trip distribution model parameters or input data (networks/skims or trip ends). Some of the typical problems that may be evident from these tests and possible calibration strategies are as follows:

- Average trip lengths too long or short: Recheck skim data and trip end inputs, recalibrate friction factors or adjust parameters of friction factor formula or logit utility equations, and/or check distribution patterns (see below).
- Coincidence ratio too low: Recalibrate friction factors or adjust parameters of friction factor formula or logit utility equations.
- District-level origin-destination patterns inaccurate for some interchanges: Check trip lengths (see above), check travel impedances between affected districts, introduce or adjust K-factors, and/or introduce impedance penalties on network links (e.g., bridge crossings).
- Too many or few intrazonal trips: Adjust intrazonal travel times for types of TAZs with this issue.
- Model too sensitive or insensitive to changes in level of service: Adjust parameters for appropriate level of service variables in impedance/utility functions or friction factors.

The ability to calibrate the origin-destination patterns using friction factors is limited, and other methods, including socioeconomic segmentation and K-factors, often must be considered. K-factors may correct for major discrepancies in trip interchanges, usually at the district level. They are typically justified as representing socioeconomic or other characteristics that affect trip making but are not otherwise represented in the model. Physical barriers, such as a river crossing, also may result in differences between observed and modeled trip patterns.

In a sense, K-factors are analogous to the alternative specific constants in logit models; they are intended to account for the choice factors that are not able to be included in the models. Since trip distribution models have relatively few input variables, it is reasonable to believe that other factors that affect location choice are not included in the models. In many cases they cannot be measured, quantified, or forecasted. K-factors provide a means for accounting for these factors, although they are then assumed to remain fixed over time and across all scenarios.

For this reason, K-factors must be used very cautiously. Because they can be used to provide nearly perfect matches between modeled and observed district-level origin-destination flows, it can be very tempting to apply K-factors to resolve differences in origin-destination flows without determining whether they are the best method to solve the problem at hand. The use of K-factors, therefore, should be considered “a last resort” after all other possible causes for error and calibration adjustments have been considered. Even when K-factors are introduced, they should be relatively small in magnitude – the closer to 1.0, the better. Complete documentation of the justification for the use of K-factors is required.

CHAPTER 7. MODELING EXTERNAL TRAVEL

The objective of the external modeling process is to develop origin-destination vehicle trip tables for trips with at least one end outside the model region. In most models, especially those for larger areas, the majority of trips are internal-internal (I-I) trips, which are both produced in and attracted to internal TAZs, that is, those TAZs within the modeling area. The trip generation process described in Chapter 5 focuses mainly on these I-I trips although care must be taken to avoid double counting of trips with only one end in the model region.

Models also include trips with one or both ends outside the region, known collectively as "external trips." These trips include:

- Internal-external (I-E) trips, which are produced inside the model region (i.e., made by residents of the region) but are attracted to locations outside the region;
- External-internal (E-I) trips, which are produced outside the model region (i.e., made by nonresidents of the region) but are attracted to locations inside the region; and
- External-external (E-E) trips, which pass through the model region but have both ends outside the region.

There are two basic steps in modeling I-E and E-I travel: trip generation and trip distribution. E-I and I-E trip generation must be performed for both the internal TAZs and external stations. For internal TAZs, the generated trips are estimated as fractions of total trips. E-E trip tables are usually estimated directly from the external travel survey data for the base year. External vehicle trips are assigned along with I-I vehicle trips in the trip assignment step, discussed in Chapter 10.

This chapter describes the policies and procedures for developing, validating, and calibrating external travel modeling components in Virginia. These are summarized in Table 7.1.

Table 7.1 External Travel Modeling Practice for Virginia Travel Demand Models

Component	Acceptable		Recommended[a]	
	Small	**Large**	**Small**	**Large**
Inclusion of transit trips	No	No	No	No (if significant transit travel across regional boundary, extending model area is preferred)
Total external trips generated	From external station counts	From external station counts	From external station counts	From external station counts

Table 7.1 External Travel Modeling Practice for Virginia Travel Demand Models (Continued)

Component	Acceptable		Recommended[a]	
	Small	Large	Small	Large
External vehicle trip types	Autos, trucks	Autos, trucks	Autos, trucks	Autos by occupancy level, trucks by type
E-E trips	Based on external survey or Big Data	Based on external survey or Big Data	Based on external survey or statewide model	Based on external survey or statewide model
Trip generation for internal TAZs	Fixed fraction of total trips	Based on distance from regional boundary	Based on distance from regional boundary	Based on distance from regional boundary
Trip distribution model form for I-E and E-I trips	Gravity model	Gravity model	Gravity model	Gravity model

Note: [a] Recommended characteristics are subject to resource constraints such as data availability and budget

7.1 Inclusion of Transit or Nonmotorized Travel

As discussed in Chapter 1, many models reflect only auto travel (trucks and passenger vehicles). It follows that in areas where it is unnecessary to model internal nonauto (transit and nonmotorized) travel, it also is unnecessary to model external nonauto travel. It also is apparent that there is little benefit to considering external nonmotorized travel in any model due to the short lengths of such trips. It is therefore both **acceptable practice** and **recommended practice** to exclude nonauto external travel from the model.

In models where internal transit travel is considered explicitly, the decision whether to model external transit travel depends on whether there is a significant number of transit trips that travel across the model boundary. In nearly all areas, the number of external transit trips is very small (or zero), and so modeling external transit travel is not worthwhile. It is relatively rare for a transit operator's service area to extend beyond the model region's boundary, even in regions with multiple transit operators. If this does occur, it is preferable to extend the model region to incorporate areas where transit service is (or is expected to be) provided. In cases where this is not feasible, the best approach would be to obtain estimates of interregional transit demand from other sources (for example, transit operator projections) and to subtract the estimated external transit demand from the total demand, rather than attempt to directly model external transit travel.

7.2 Modeling of Vehicle Trips

Since modeled external travel will include only auto trips (trucks and passenger vehicles) in nearly every case, it makes sense to model these trips as vehicle trips rather than person trips. While vehicle occupancy can vary for different external travel corridors, the information to model vehicle occupancy would have to include information on areas outside the model region which is generally unavailable. It is therefore both **acceptable practice** and **recommended practice** to model external travel as vehicle trips.

Modeling external travel as vehicle trips has the advantage of being consistent with traffic count data used to estimate the total amount of external travel. Generally, the total number of external vehicle trips is equal to the sum of traffic counts for all external stations (in forecast years, with growth factors applied), noting that E-E trips are counted twice in this sum. This is discussed further below.

7.3 General Process for Modeling External Travel

The general process for modeling external travel is summarized as follows:

1. Determine total number of external vehicle trips using traffic counts at external stations (in forecast years, with growth factors applied).
2. Separate the vehicle trips by external station into truck trips (by truck type) and auto trips. If internal auto trips are segmented by vehicle occupancy level, then external auto trips should be segmented the same way.
3. Determine the percentages of external truck trips by type and external auto trips that are E-E, E-I, and I-E trips (by external station if survey data are available).
4. Create E-E auto and truck vehicle trip tables.
5. For each internal TAZ, estimate the number of E-I and I-E truck trips by type and auto trips by occupancy level so that the regional totals are maintained.
6. Distribute E-I and I-E trips between external stations and internal TAZs and create E-I and I-E vehicle trip tables.
7. Segment all external trip tables by time-of-day period (consistent with the highway assignment process).

These steps are discussed in the subsections that follow.

7.3.1 Determining External Vehicle Trips by External Station

For the base year, the number of daily vehicle trips for each external station is equal to the annual average weekday daily traffic (AAWDT) count for that station. The total number of external vehicle trips for the region is therefore equal to the sum of the traffic counts for all external stations. If traffic counts are available for every external station, these counts should be used; if counts are unavailable for some stations, vehicle trips must be estimated for those stations. For forecast years, growth factors are typically applied to the base-year vehicle trips. These growth factors, which can vary by external station, should consider the expected growth in the model region as well as the areas served by the roadways comprising the external stations. It is important to note that E-E trips are counted twice in this total of external vehicle trips while E-I and I-E trips are counted only once.

7.3.2 Segment External Vehicle Trips by Classification and Occupancy

As discussed in Chapter 8, truck trips are considered separately in travel models, typically by truck type (e.g., small, medium, and large). This segmentation applies to external trips and the external trip generation and distribution processes as well. This requires that the external vehicle trips by external station be segmented into trucks by type and autos. This segmentation is most often achieved using vehicle classification counts at the external stations. For those external stations where classification counts are unavailable, vehicle trips may be segmented using classification information from other similar roadways.

If the highway assignment process segments auto trips by vehicle occupancy level (e.g., SOV, HOV2, etc.), then external auto trips must be segmented the same way for assignment. This requires that the external auto trips by external station be segmented by occupancy level. This segmentation is most often achieved using data from the external travel survey at the external stations. For those external stations where survey data are unavailable, auto trips may be segmented using occupancy information from other similar roadways or regional averages.

7.3.3 Segment External Station Trips by Type of External Travel

The total trips by vehicle type for each external station are segmented to represent the number of E-E, E-I, and I-E trips. External travel survey data are the best source to develop segmentation percentages. When survey data are not available, Big Data such as mobile location data and GPS data, as discussed in Section 4.2.2, can be used to estimate the proportions of trips that are E-E and E-I/I-E at each external station. Another source of data is the Virginia Statewide Transportation Model (VSTM), which can be used to extract a subarea trip table for a region. However, the VSTM may not have the same level of network detail as a regional model, and thus some external stations in a regional model may not correspond to nodes in the VSTM. When all these sources are not available or are missing for some external stations, manual segmentation at external stations may be used, which involves some estimation and judgment on the part of the model developer. Often, these percentages are estimated using experience from other areas. For example, in the Richmond/Tri-Cities model region, the percentages shown in Table 7.2 are applied to external stations by roadway facility type [40].

Segmentation for E-E, E-I, and I-E trips can differ by vehicle type (as shown in Table 7.2), with survey data (if available) again being the best data source for such segmentation. Given the current data availability, it is **recommended practice** to use Big Data such as Location-Based Service data or GPS data to develop segmentation of external trips at external stations.

Table 7.2 External-External Trip Percentages by Roadway Type

Facility Type	Passenger Car Percentage	Heavy Truck Percentage
Interstate	23	23
Minor Freeway	17	13
Principal Arterial	14	9
Major Arterial	9	5
Minor Arterial	7	1
Major Collector	0	0
Minor Collector	0	0
Local	0	0

Source: AECOM, "Richmond / Tri-Cities Model Update Technical Memorandum," 2020 [40]

7.3.4 Creating External-External Trip Tables

The methods for generating external-external travel can be classified into three general types:

- Iterative proportional fitting (IPF) of E-E trip tables;
- Developing origin-destination factors from external travel survey data; and
- Obtaining information from a model of a larger area, such as a statewide model that includes the model area.

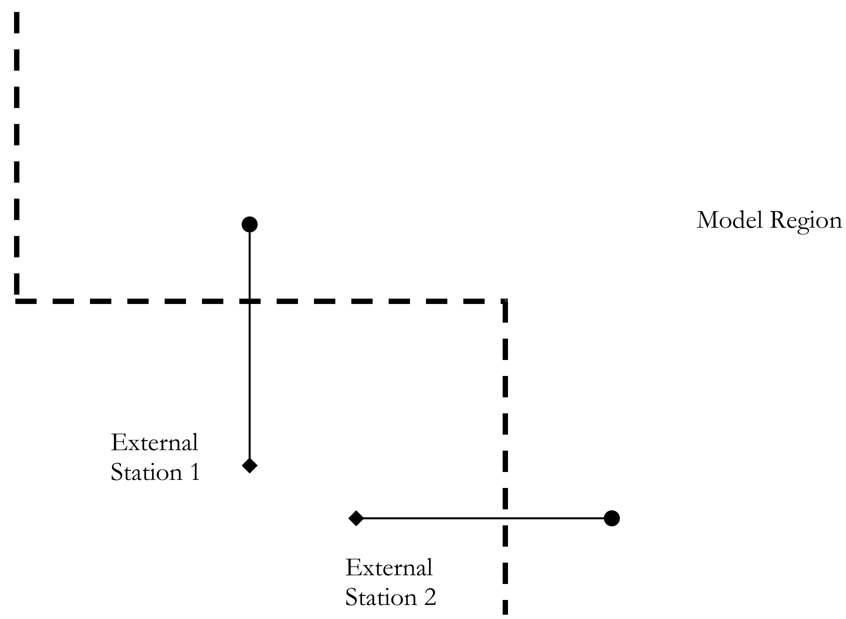
Iterative Proportional Fitting (IPF) of E-E Trip Tables

The IPF process uses a "seed" distribution and iteratively adjusts the cell values until a good match between the target row and column totals is achieved [41]. For E-E trip tables, the row and column total targets represent the portions of the external station productions and attractions described in Section 7.1.3 that are through trips.

To produce optimal results, the seed for the IPF process should reflect the expected distribution of E-E trips between external stations. A seed E-E trip table can be derived from an external travel survey, Big Data, or the VSTM. Given the current data availability, it is **recommended practice** to use Big Data such as Location-Based Service data or GPS data to develop a seed table for external trips at external stations.

However, in the absence of these data sources, or when data are missing for some external stations, developing the seed matrix may involve some judgment on the part of the model developer. A seed table with the same value in each cell of the table would be valid, but different values can usually be used to improve the process. First, a value of zero should be used for any external station pairs between which travel is unlikely to occur. A hypothetical example of such a case is shown in Figure 7.1, where no trips should be permitted between External Stations 1 and 2. Next, relatively higher values should be used in the seed matrix for external station pairs between which a high volume is expected, such as stations representing the points at which the same interstate highway enters and leaves the region.

Figure 7.1 Example of External Stations with No Travel Between Them



When the seed table and the targets have been established, the IPF process can be performed using modeling software or a spreadsheet.

Developing Origin-Destination Factors from External Travel Survey Data

If data from a local external travel survey are available, and the survey's sample size is sufficient, an E-E trip table can be estimated from the expanded survey data. Alternately, the percentage of trips produced by each external station that are attracted to each other station can be obtained and applied to the external station trip productions to create an E-E trip table. These percentages should be applied separately by vehicle type (auto and each truck type). Because the survey data represent the base year (or a recent year), this process is used only for base-year E-E trip tables. In this case, forecast year tables are generally created through an IPF process, using the base year trip table as the "seed."

Developing Origin-Destination Tables from Big Data

External travel can be estimated from some LBS datasets if the parameters used in extracting data for the region or state are appropriately defined so that trips from and to outside of the region are included. Importantly, LBS data can provide estimates of the geographic distribution of trips inside the region to/from each external station as well as temporal distributions of travel. Verification of appropriate expansion is critical, which can be done using external station counts. An E-E trip table is created using the IPF procedure described above, with traffic counts for the external stations and E-E trip proportions that can be derived from the LBS data.

Like LBS data, travel into and out of the region can be tracked with GPS tracking data. The advantage of the GPS tracking data is that the actual route used is known, so there is no need to infer to the entry or exit station that was used. LBS data, on the other hand, is only useful in identifying trip ends, and thus, external station must be inferred using a routing algorithm of some kind. As noted above for LBS data, GPS tracking data cannot necessarily replace counting stations at external stations, as these data will only provide a sample of trips. Expansion of the sample to the universe is necessary, with the traffic counts at the external stations used as marginal controls.

The process of deriving O-D table generally takes the following steps:

- Define external stations for use in obtaining the Big Data from a data vendor;
- Process origin-destination data, including location-based service data for personal travel and GPS data for commercial/truck travel;
- Develop daily trip tables and time period trip tables for personal travel and commercial/truck travel;
- Compute the proportions between through trips (E-E) and trips with a trip-end at an internal TAZ (E-I and I-E trips), using the Big Data;
- Segment the external station traffic volumes into E-E and E-I/I-E trips; and
- Conduct iterative proportional fitting (IPF) for E-E personal trips using those previously calculated E-E trip ends at external stations as controls and Big Data O-D table as the seed tables

Obtaining Information from a Model of a Larger Area

The Virginia Statewide Transportation Model (VSTM) can be used to produce E-E trip tables for any models whose regions lie entirely within Virginia. This can be done using the process commonly used for creating subarea trip tables in a regional model. As is typical for subarea models, the level of zonal resolution is usually finer for regional models than for the VSTM, and so a disaggregation process for the VSTM trip tables is required. Because subarea trip tables are dependent on the highway assignment results for the larger model, adjustments to ensure consistency with the target external station volumes are performed, often done using an IPF process.

The process for creating E-E trip tables from the VSTM can be summarized as follows:

1. Define a subarea of the VSTM corresponding to the regional model's analysis region, with the links defining the subarea cordon corresponding to the regional model's external stations.
2. For each vehicle type (auto and truck), create a trip table for this subarea using the modeling software.
3. Adjust the trip table for each vehicle type using an IPF process where the row and column targets are the external station target volumes for the vehicle type, and the seed trip table is the table from the subarea extraction process.
4. Create a correspondence between the VSTM TAZs and the regional model TAZs.
5. For each regional model TAZ, determine the percentage of travel in the VSTM TAZ by vehicle type for the regional model TAZ. This fraction is the percentage of trips in that TAZ in the regional model trip table of the trips for all TAZs lying within the VSTM TAZ in which the regional model TAZ is located.
6. Apply these percentages to the trip table created in Step 3 to create the E-E trip table for the regional model.

7.3.5 Determining E-I and I-E Trips for Internal TAZs

The trip generation process described in Chapter 5 estimates the total number of person trips generated in each internal TAZ. Experience and logic dictate that the closer a TAZ is to the model region's boundary, the higher the percentage of travel that is external to the region. It is therefore both **acceptable practice** and **recommended practice** to relate the I-E/E-I share of total trips to the TAZ's distance from the regional boundary. Often, the highway distance to the nearest external station is used. As an example, the Richmond/Tri-Cities model Base 2017 uses Equations 7-1 and 7-2 to estimate the shares of I-E trips for internal TAZs [40]:

$$\text{I-E share for work trips} = 0.438 * (\text{Distance} \wedge -1.8) \quad (7\text{-}1)$$

$$\text{I-E share for non-work} = 0.8 * (\text{Distance} \wedge -2) \quad (7\text{-}2)$$

Where "distance" refers to the highway distance from the TAZ to the nearest external station in miles.

The parameters of these types of equations can be estimated from external travel survey data if available. Big Data, like LBS O-D data, can also be used to estimate these equations. It should be noted that separate functions can be used for I-E and E-I trips although when no local survey data are available, the same equation may be used for both E-I and I-E trips (as is done in Richmond/Tri-Cities). It also should be noted that while it is possible to segment external trips by work and nonwork purposes, it is not necessary to do so. Even if external trips are not segmented by purpose, separate equations by trip purpose, such as Equations 7-1 and 7-2, may be used for the purposes of determining the total E-I and I-E trips for internal TAZs from the trip generation results.

Two other steps are necessary to complete the process of determining E-I and I-E trips for internal TAZs. First, since the trips estimated in the trip generation process are person trips, they must be converted to vehicle trips for use in E-I and I-E trip distribution models. This process is straightforward and uses vehicle occupancy rates derived from external travel surveys, household travel surveys, or other data sources such as NHTS. Second, a normalization process is needed to ensure that the total numbers of I-E and E-I trips generated in internal TAZs equal the total trips generated at external stations, as determined by the process discussed in Section 7.1.3. This may involve adjusting the parameters of formulas such as Equations 7-1 and 7-2 or by adjusting the outputs for I-E trips to match the totals for the external stations.

7.3.6 E-I and I-E Trip Distribution

The processes described in Sections 7.1.3 and 7.1.5 produce E-I and I-E vehicle trip ends for each external station and each internal TAZ. A trip distribution process uses these as inputs to create the E-I and I-E vehicle trip tables. It is **acceptable practice** for all model areas to use the gravity model (see Section 6.1.1) for E-I and I-E trip distribution. Highway travel time is used as the impedance measure for E-I and I-E trip distribution. The friction factors may be fitted to the observed trip length frequency distributions (if external travel survey data are available), transferred from another region or a previous model version, or fitted to functions such as the exponential gamma functions.

7.3.7 Segmenting external trip tables by time of day

Because the E-E, E-I, and I-E vehicle trips are assigned along with the internal auto and truck vehicle trips, the time-of-day segmentation for external trips must be consistent with that for internal trips. It is both **acceptable practice** and **recommended practice** to factor external vehicle trip tables using fixed factors derived from traffic counts at external stations. If the temporal counts are not available at some external stations, temporal distribution of trips from Big Data can be used to derive factors.

7.4 External Travel Validation

7.4.1 Data Sources for Validation

The main validation checks for external travel models involve comparisons of model results to observed travel patterns. The main data source for validation is therefore the external travel survey data set, if available. The household travel survey provides information on I-E trips, but not E-E or E-I travel.

7.4.2 Validation Checks

It should be noted that external travel models are designed to match the trip inputs at the external stations, and so checks of these volumes are unnecessary. It is not possible to estimate the actual number of E-I and I-E trips generated in internal TAZs due to the low incidence of such trips in most cases and the small sample sizes of external travel surveys.

Table 7.3 summarizes the model validation checks for trip distribution models.

Table 7.3 External Travel Validation Procedures for Virginia Travel Demand Models

Type of Check	Model Region Size	
	Small	Large
Average trip length by vehicle type	Within 10%	Within 10%
Trip length (time and/or distance) frequency distribution – coincidence ratio	>0.60	>0.60
External-to-district/district-to-external trip flows	Reasonableness check only	Reasonableness check only

Average Trip Length by Vehicle Type

As discussed in Section 6.2.2, similar to the checks for internal travel models, the average trip lengths and the shapes of the trip length frequency distributions from the model are compared to observed data if available. Average trip lengths and trip length frequency distributions for the observed condition are computed directly from the trip tables obtained from the expanded survey data and compared to trip table information obtained from applying the model.

Because of the smaller number of trips associated with external travel, error ranges are higher than those associated with internal travel, and the guidelines for comparisons with observed data are less strict. Generally, the modeled average trip lengths for each vehicle type should be within 10 percent of observed. Depending on the segmentation used, some vehicle types (e.g., heavy trucks) may have relatively few trips, and so the 10 percent guideline can be relaxed in these cases.

Trip Length Frequency Distribution by Purpose

As described in Section 6.2.2, visual checks of trip length frequencies can be useful; the observed and modeled trip length frequency distributions can be plotted on the same graph to see how closely the distributions match. Coincidence ratios (see Section 6.2.2) can be used. The guideline for external travel is for the coincidence ratio for each vehicle type to be at least 60 percent.

External to District/District to External Trip Flows

While the concept of "districts" is not applicable to external stations, comparisons can be made of modeled and observed travel between districts comprised of internal TAZs, which may be based on jurisdictions, and groups of adjacent external stations, or individual stations with higher volumes. These comparisons are reasonableness checks, and there are no specific guidelines for what constitutes a satisfactory match between modeled and observed data. The low sample sizes for external travel surveys make it difficult to specify such guidelines.

7.4.3 Model Calibration and Troubleshooting

Issues discovered during the model checks described above may imply errors in:

- E-I/I-E internal TAZ trip generation model parameters;
- E-I/I-E trip distribution model parameters;
- E-E trip tables; or
- Input data.

Some of the typical problems that may be evident from these tests and possible calibration strategies are as follows:

- Average trip lengths too long or short: Recheck trip end inputs, recalibrate friction factors or adjust parameters of friction factor formula, and/or check distribution patterns (see below).
- Coincidence ratio too low: Recalibrate friction factors or adjust parameters of friction factor formula.
- District-level origin-destination patterns inaccurate for some interchanges: Check trip lengths (see above); check travel impedances between affected districts.

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CHAPTER 8. TRUCK AND FREIGHT MODELING

8.1 Background

The person trips generated in the trip generation step (see Chapter 5) and the external travel discussed in Chapter 7 comprise most, but not all, travel in a region. Trucks and other commercial vehicles are an important segment of the travel market for major regional models.

There is a difference between *truck models* and *freight models*. The difference is that freight models also may include nonhighway modes, such as rail and water, and that truck trips may include nonfreight-related activities. While trucks are the mode carrying most of the freight tonnage in the U.S., trucks also are used to perform services; to do maintenance; to carry construction materials and equipment; depending on the definition of freight, to deliver local (e.g., last mile) freight; and to do the repositioning of empty or partially loaded trucks that are necessary so that trucks are available to carry loads of long-distance freight. This distinction is important because, according to the Federal transportation regulations, VDOT and MPOs are required to consider freight, as distinct from trucks, in their transportation planning. But estimates of the volume and performance of all trucks may be necessary to support other planning efforts, such as infrastructure, energy, or environment planning.

Additionally, the truck counts collected by VDOT and others will include both freight and nonfreight activities. Those counts cannot classify trucks as engaged in carrying freight or engaging in some other purposes. Nonfreight activities are highly correlated with population. So, as the size of an urban area increases, the share of all truck travel for nonfreight activities increases. Conversely in rural areas between metropolitan urban areas, freight activities may represent the majority of the travel by trucks.

The FHWA Freight Analysis Framework Version 4 (FAF4) loaded highway network [46] can be used to make an estimate of the vehicle-miles traveled (VMT) that is attributed to all vehicles, to what the FAF considers to be freight in trucks, and all travel by trucks, for the entire U.S., for all of Virginia, and for the FAF regions in Virginia. The FAF4 metropolitan regions are similar to MPOs, but do not share precise boundaries. Also, the FAF includes only the higher functionally classified roads. The results are shown in Table 8.1.

The figures in Table 8.1 are not intended to serve as model validation targets. The roads included in the FAF network are not the same as those included in models used in Virginia; the boundaries of the FAF regions are not the same as the model regions; and the trucks in FAF are not necessarily the same as the trucks in travel demand models. Table 8.1 is intended to show that all trucks do not carry freight, at least freight as defined by the FAF, and that the percentage of a region's truck travel that is freight depends on the size of the region (e.g., regions with larger populations have more nonfreight trucks and thus a lower share of freight trucks) and the location of the region (e.g., Hampton Roads is not on a major through traffic corridor, and thus has a lower share of FAF freight trucks than does Richmond, which is on the I-95 Corridor).

Table 8.1 FAF All and Truck VMT by FAF Regions (2012)

	Total Daily VMT (thousands)	Total Daily Truck VMT (thousands)	Truck Percentage of Daily VMT	Total Daily FAF Truck VMT (thousands)	FAF Trucks as Percentage of All Trucks
U.S.	5,247,664	575,911	11%	290,327	50%
Virginia	147,459	11,825	8%	7,305	62%
Washington, D.C.-Maryland-Virginia	85,118	5,545	7%	1,815	33%
Virginia portion of Washington, D.C.	40,230	2,044	5%	1,120	55%
Richmond area	26,123	1,977	8%	1,220	62%
Virginia portion of Virginia Beach-Norfolk area	24,444	1,000	4%	447	45%
Virginia non-metropolitan	56,575	6,805	12%	4,519	66%

Source: Cambridge Systematics analysis of the FAF4 Highway Network.

The remainder of this chapter discusses truck and freight modeling practices relevant to Virginia.

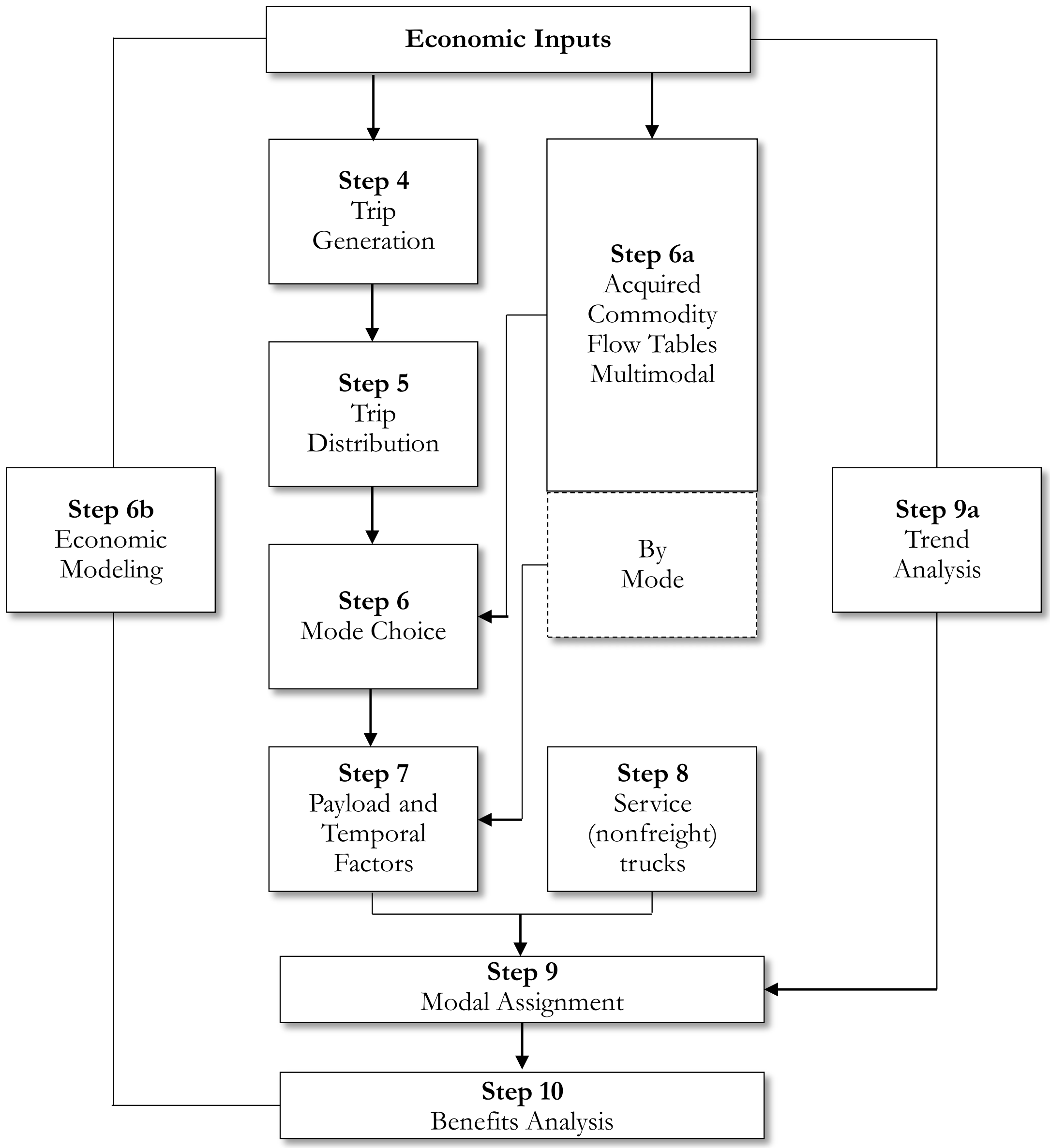
8.2 Truck and Freight Modeling Practice

8.2.1 Statewide Freight Models

This section discusses statewide freight models, which often provide inputs to MPO truck models.

All travel demand models, including truck models, require trip tables between TAZs and networks that connects these TAZs. Freight models include tables of freight shipments between TAZs, and the modal networks that connect those TAZs. In multimodal freight models, the flow unit in the tables may be annual tons, but when assigned as trucks on a highway network, these flows are typically converted to daily truck vehicle trips between TAZs. *NCFRP Report 8, Freight Demand Modeling to Support Public Sector Decision-Making* [47] presents a framework for freight models as shown in Figure 8.1. (The numbered steps in Figure 8.1 refer to the steps in *NCFRP Report 8*, Chapter 4.)

Figure 8.1 Freight Model Framework

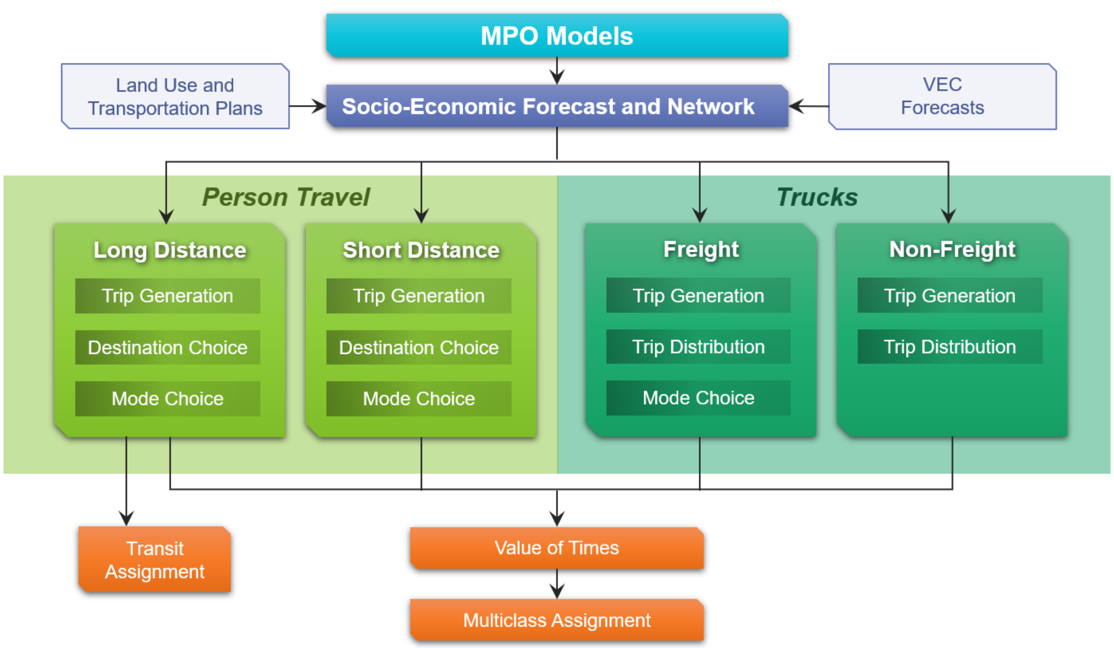


Source: Cambridge Systematics, Inc., "Freight Demand Modeling to Support Public Sector Decision-making, NCFRP Report 8," 5, Figure 5.2, 2010 [47].

The two paths in the middle of Figure 8.1 (the path beginning with Step 4 and the path beginning with Step 6a) differ only in how the freight trip table is developed. That table may be developed through the direct acquisition of a commodity flow table (Step 6a), or the table may be developed through a "four-step" trip process similar to what is used in passenger modeling (Steps 4, 5, and 6). If the freight model only deals with flows by truck, then the freight model involves only a single mode, and the mode choice step is not necessary. As shown in Step 7 of Figure 8.1, if the commodity flow or multimodal table is expressed as annual tonnage, flows are converted from annual tons by truck to average daily trucks using an annual to daily conversion factor and a factor of payload (tons) per truck by commodity. *NCFRP Report 8* suggests the use of 295 to 300 as the annual to average weekday factor. The Quick Response Freight Manual (QRFM) [48] suggests a range of payload factors, with the factors to be used dependent on both the local economy and the commodities included in a freight model. In addition to the QRFM source, FHWA also issued a report, *Development of Truck Payload Equivalent Factor* [49], which provides state-specific factor estimates which may be for converting measures of tons into numbers of trucks. Step 8 in Figure 8.1 reinforces that truck models should include both freight and other trucks.

While freight truck volumes and their performance can be observed locally, the behaviors creating freight truck tables are national (or international). The factors that cause the production (origins) of freight shipments and the attraction (destinations) of freight shipments and the networks used to travel between these TAZs are therefore national in scope. While it might be appropriate for statewide models to consider these factors, it is not practical for an MPO model to forecast behaviors far beyond its own region. Additionally, while freight behavior (including that by trucks) may be national, the travel by nonfreight/service/other trucks is influenced by local behavior. For that reason, it is not typically necessary for service trucks to be shown as traveling from large TAZs outside of the principal model region. Those service trucks that begin or end outside of the region can be loaded at external stations on the boundary of the model region.

Figure 8.2 Virginia Statewide Transportation Model Framework

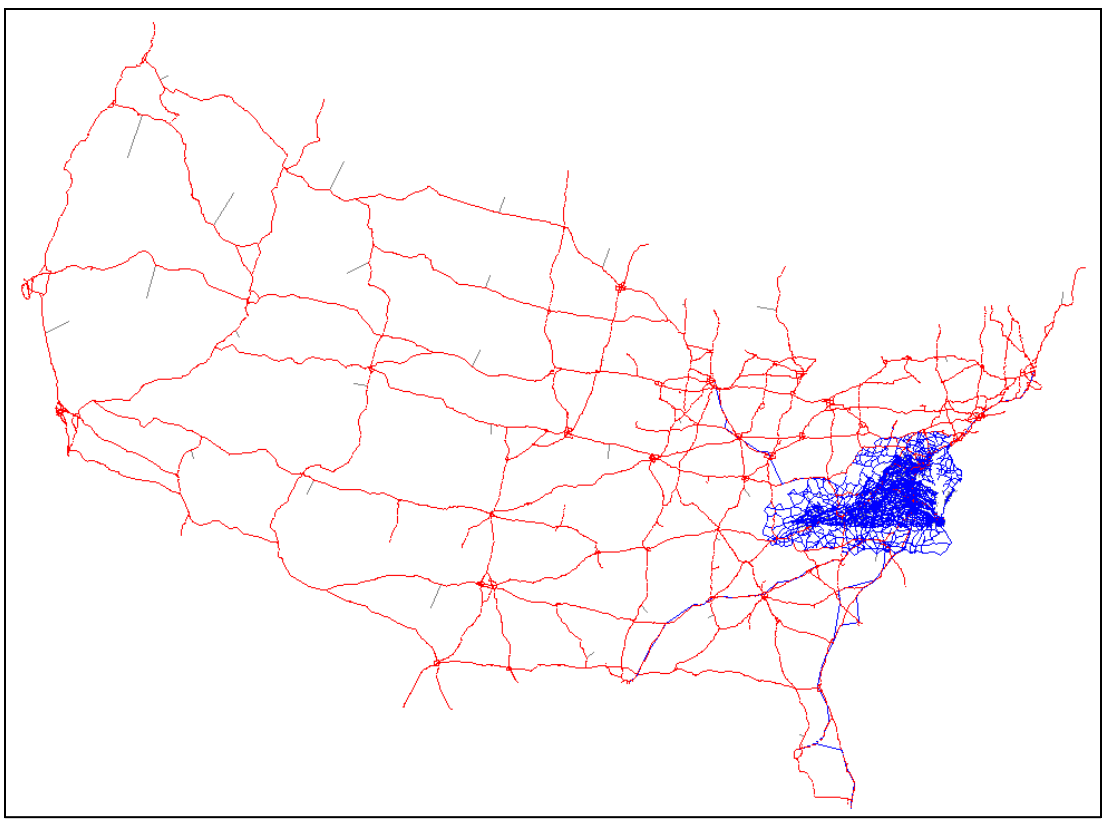


Source: Adapted from Cambridge Systematics, Inc., "Virginia Statewide Transportation Model: VSTM Version 1.0 Final Report," 1-3, Figure 1.1, 2017 [50].

The Virginia Statewide Transportation Model (VSTM) is a modeling system of passenger and freight/non-freight truck travel in the Commonwealth of Virginia and its surrounding areas (Figure 8.2) [50]. A key feature of the VSTM is the consistent framework for representing short and long distance passenger travel markets in terms of using the logit-based model structure to model trips generated and destination choices of these trips (travel patterns), which allows flexibility and use of accessibility measures and socioeconomic variables. The intra-state truck trip model was developed on the basis of GPS-based truck travel data, and TRANSEARCH data was used as the estimation database to develop a freight model that is sensitive to changes in the economy and demography of Virginia. A value of time segmentation is implemented in the assignment processes to reflect the sensitivity of tolls in route choice between toll and non-toll facilities.

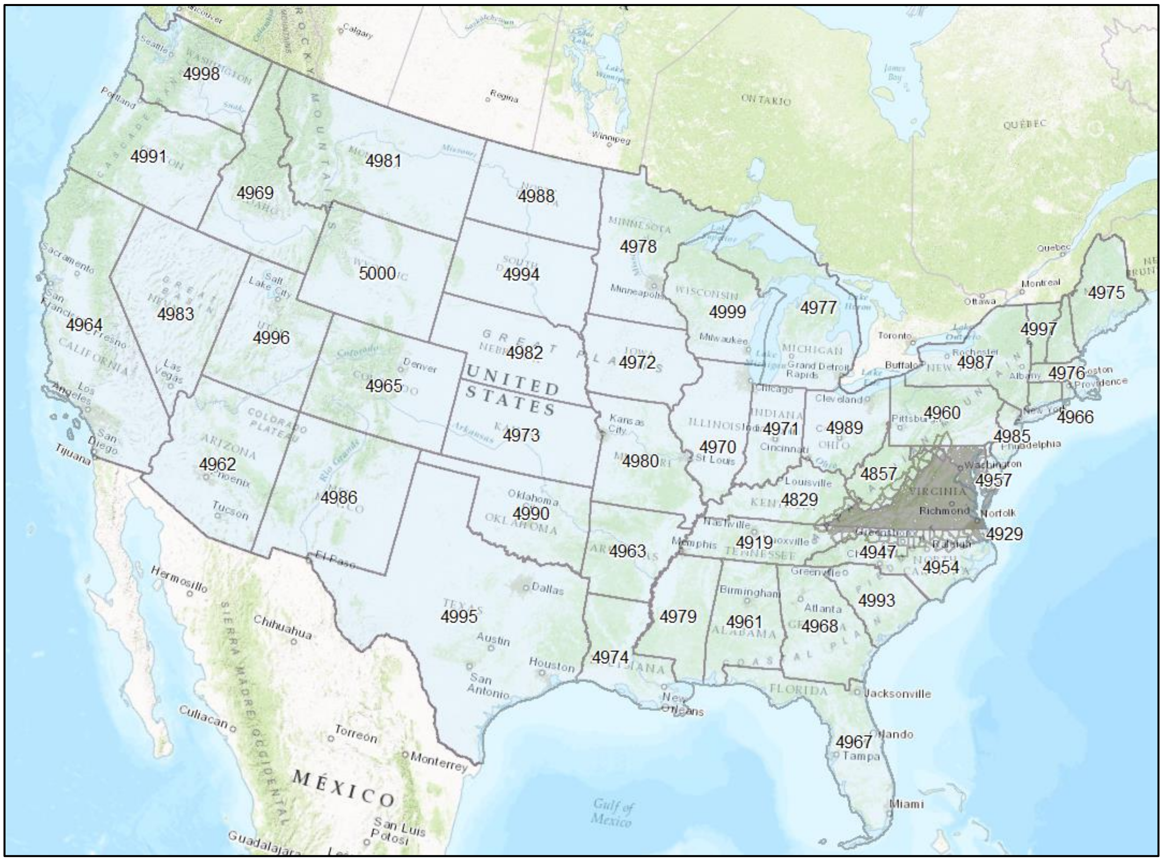
As shown in Figure 8.2, the VSTM has both freight and non-freight modeling processes, following conventional trip-based modeling processes as outlined in Figure 8.1. For the Continental US, the highway network in the VSTM is shown in Figure 8.2, and macro zones are displayed in Figure 8.3. For the Commonwealth of Virginia and adjacent areas, the VSTM highway network is exhibited in Figure 8.4, and the VSTM zones are illustrated in Figure 8.5.

Figure 8.3 VSTM Highway Network of Continental U.S.



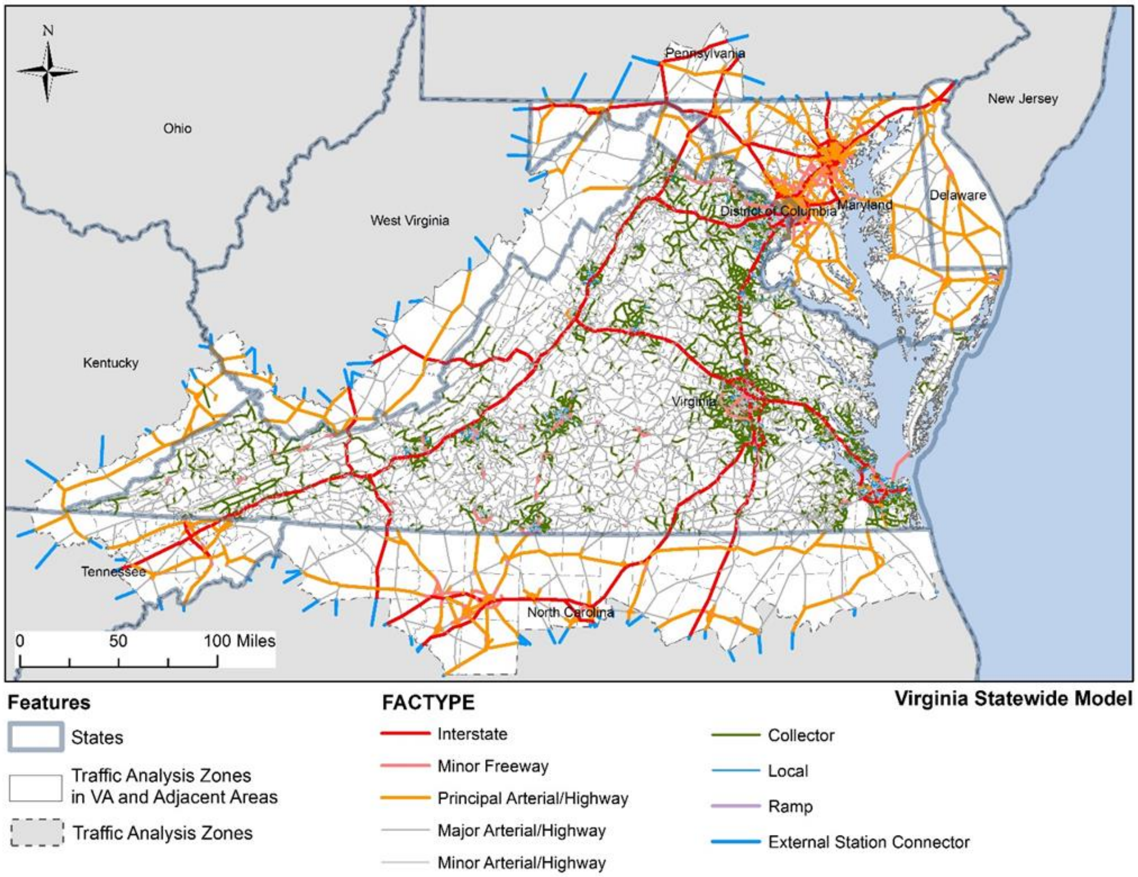
Source: Cambridge Systematics, Inc., "Virginia Statewide Transportation Model: VSTM Version 1.0 Final Report," 5-16, Figure 5.3, 2017 [50].

Figure 8.4 VSTM Zones of Continental U.S.



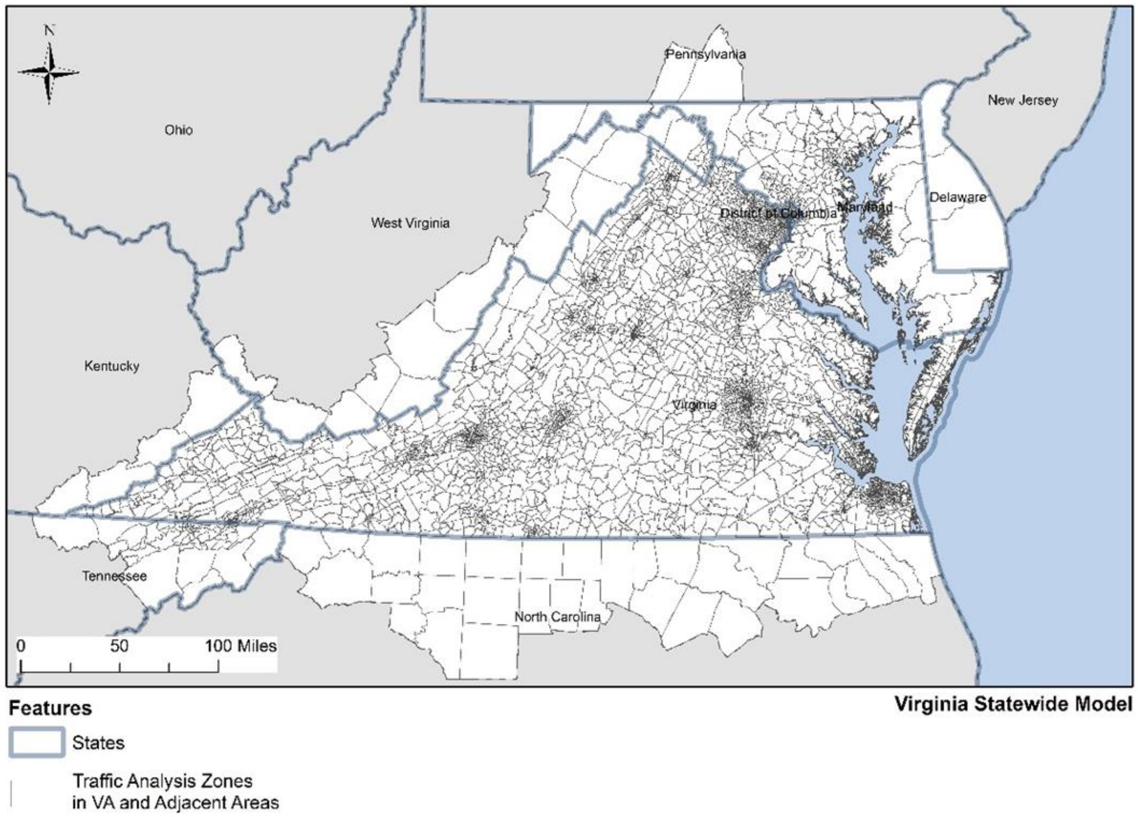
Source: Cambridge Systematics, Inc., "Virginia Statewide Transportation Model: VSTM Version 1.0 Final Report," 5-15, Figure 5.1, 2017 [50].

Figure 8.5 VSTM Highway Network in Virginia and Adjacent Areas



Source: Cambridge Systematics, Inc., "Virginia Statewide Transportation Model: VSTM Version 1.0 Final Report," 3-2, Figure 3.1, 2017 [50].

Figure 8.6 VSTM Zones in Virginia and Adjacent Areas



Source: Cambridge Systematics, Inc., "Virginia Statewide Transportation Model: VSTM Version 1.0 Final Report," 2-3, Figure 2.1, 2017 [50].

"Four-Step" Freight Models

As noted above, the VSTM uses a commodity table as an estimation data set to develop the trip table produced in the first three steps of traditional four-step trip model. In these types of freight models, the number of commodities is reduced to a more manageable number (typically approximately a dozen) that are consistent with the state's economy, specifically 16 commodity groups (CG) in the VSTM. The freight model forecasts these multimodal CG trip tables based on transportation and socioeconomic data that is specific to Virginia.

Freight Trip Generation

The forecast variables for the trip generation for internal state TAZs reflect the detailed industry employment (typically NAICS employment) for those state TAZs. A series of commodity flow generation equations was estimated through linear regressions of the annual commodity flow productions from TRANSEARCH data and the population and NAICS employment at the county level, which is the common unit of geography for which the commodity, population, and NAICS employment data are available. The relationships established at the county level are applied to TAZ-level data. The explanatory variables tested within the production regression models included employment by NAICS code. The production equations were fit to the TRANSEARCH observed annual tonnage for 12 of the 16 CGs, as shown in Table 8.2, with the remaining four treated as special generators. The attraction equations were fit to observed annual tonnage for all 16 CGs, using employment or total population as explanatory variables.

Table 8.2 Production Equations by Commodity Group in the Virginia Statewide Transporation Model

Commodities		Coefficient (Annual Tons per Employee)	Variable Name (NAICS Employment)
Code	Name		
1	Agriculture products	1,144.60	11
2	Grains, alcohol, and tobacco products	598.72	11
3	Stones, non-metallic minerals, and metallic ores	259.75	
4	Natural sands	13.70	
5	Gravel and crushed stone	1,799.08	
6	Coal	7,715.87	2121
7	Fuel products	2,753.60	324
8	Coal and petroleum products, n.e.c.	488.14	324
9	Pharmaceutical and chemical products	287.22	325
10	Other nondurable manufactured goods	21.97	31 & 32 NEC
11	Logs, paper, printed material	86.67	
12	Wood products	140.63	321
13	Non-metallic mineral products	919.49	327
14	Durable manufactured goods	30.83	33 NEC
15	Waste and scrap	2.82	EMP Total
16	Mixed freight	4.84	EMP Total

Note: CG 3,4,5,11, are special generators. North American Industry Classification System (NAICS) is the standard used by Federal statistical agencies in classifying business establishments.

Source: Adapted from Cambridge Systematics, Inc., "Virginia Statewide Transportation Model: VSTM Version 1.0 Final Report," 6-4, Table 6.2, 2017 [50].

Freight Trip Distribution

Freight trip distribution follows the same concepts discussed in Chapter 6, Trip Distribution. Productions are distributed to attractions using the gravity model where the friction factors use a negative exponential function of distance. Distance is assumed to be a good explanatory variable because freight shipment cost is highly correlated with it. The coefficient of the negative exponential friction factor is equal to the average trip length, which can be measured separately for each commodity being transported. In the VSTM, the average trip lengths that are needed to obtain trip length frequency distributions and the associated friction factors were obtained for truck modes from the TRANSEARCH data. For the other freight modes, distances mileages were taken from the County to County Distance Skims reported by the Oak Ridge National Laboratory's (ORNL) Center for Transportation Analysis.

Freight Mode Choice

As discussed in Chapter 9, Mode Choice, the percentage of trips between TAZs choosing each mode is typically forecast using a logit formulation. The utility equations include constant terms which account for all impacts not considered by the utility variables. The most important variables in freight mode choice have been found to be travel time, travel cost, and the reliability of travel. The problem in freight forecasting is that the utility constants are large compared to the variable portion of utility. The constants account for such considerations as existing business practices and relationships. The difficulty of estimating the constants is eliminated by using an incremental or pivot point logit equation. In this application the changes in utility are applied to the existing mode shares. Since the existing mode shares already include the considerations of the unknown utility constants, by taking the differences in utilities between existing and alternative conditions, the constant terms cancel out. Thus forecasts can be made using changes in the utility variables, assuming that all other conditions remain the same.

The VSTM freight mode choice model is an incremental mode choice model. As such, it requires a table of existing mode shares. The required table of existing mode shares is developed directly from the table of modal freight tonnage flows, by origin, destination, commodity group, and mode. The truck mode is the most dominant mode, carrying 74 percent of all freight in the Commonwealth, followed by intermodal and carload rail at 22 percent and 2 percent, respectively. As expected, the share of freight being transported by water and air are very small – 2.0 and 0.026 percent, respectively.

The incremental logit model takes the form shown in Equation 8-1.

$$\mathrm{S}_{\mathrm{ijm}}^{'} = \frac{S_{ijm} * \exp\left(\Delta U_{\mathrm{ijm}}\right)}{\sum_{m}^{M} S_{ijm} * \exp\left(\Delta U_{\mathrm{ijm}}\right)} \qquad (8\text{-}1)$$

where,

S'_{ijm} = New share of the flows carried by mode *m* between TAZ *i* and TAZ *j*,
S_{ijm} = Existing share of the flows carried by mode *m* between TAZ *i* and TAZ *j*,
U_{ijm} = Utility from *i* to *j* of mode *m* among all modes *M*, which also is stated as
= Modal Constant $_m$ + b^v * $ExplVar^v_{ijm}$;

where

b^v = Coefficient for ExplVar *v* (e.g., travel time); and
$ExplVar^v_{ijm}$ = Explanatory Variable *v* (e.g., travel time) for mode *m* between TAZ *i* and TAZ *j*;

Freight Assignment

The highway assignment step, which is described in Chapter 10, is where the modal vehicle trip tables are loaded to their respective networks. However, the assignment of freight trucks on highway networks does not necessarily follow the rules of passenger vehicle assignments. As a result, freight trucks are often preloaded to minimum distance routes before autos and other vehicles are assigned in a user equilibrium.

While the interaction of trucks and autos sharing highways does determine the speed and performance for all vehicles, freight trucks operate to maximize profit, and not necessarily to minimize travel time. The simplifying assumption in equilibrium highway assignment of perfect knowledge of the highway system may be more problematic for long distance freight trucks, whose drivers may not have the local knowledge of alternative routes. Additionally, some routes may have height, width, or turning radius restrictions that do not allow for the passage of large freight trucks. Trucks can (and should) be restricted from certain highway links, such as auto-only parkways.

For many freight operators, truck revenue is restricted to a distance between an origin and a destination as agreed by the carrier and the shipper/receiver, and time costs are relatively small. Thus, freight trucks may have little incentive to use longer, faster routes, especially considering that trucks use more fuel than autos. Similarly, if those longer, faster routes are tolled, there may be little usage incentive.

Subarea Extraction from the Statewide Model for MPO Regions

For MPOs whose model regions are geographically within Virginia, the VSTM may be used to produce better estimates of truck volumes at the external stations of the MPO model region. If the VSTM includes more truck segments than the MPO model, applying information from the more detailed segmentation to the more limited truck segments in the MPO model may be considered. This may be done using the standard techniques of subarea extraction available in modeling software.

Typically, the TAZs of the MPO model will nest within the TAZ structure of the VSTM. The productions and attractions for each truck table can thus be computed for each MPO model

TAZ. The percentage shares for productions and attractions for each MPO model TAZ in the corresponding VSTM TAZ can be used to expand the windowed truck tables. These truck trips can be used directly and validated in the MPO model truck trip tables. Alternately, the windowed and expanded truck trips can be used to calculate the percentages for each VSTM truck travel segment in the MPO model, and the percentages can be applied to the MPO model truck trip tables.

8.2.2 MPO Models

Truck Models (Including Service Trucks)

The policies and procedures for trip distribution practice in Virginia are summarized in Table 8.3.

Table 8.3 Truck Modeling Practice for Virginia MPO Travel Demand Models

Component	Acceptable		Recommended[a]	
	Small	**Large**	**Small**	**Large**
Truck trip generation	Transferred truck trip generation parameters or use of GPS data as expanded and related to land use	Transferred truck trip generation parameters or use of GPS data as expanded and related to land use	Transferred truck trip generation parameters	Parameters estimated from commercial vehicle survey
Treatment of ports and terminals	Special generators	Special generators	Special generators	Special generators
Truck trip distribution	Gravity model or travel patterns of expanded GPS data	Gravity model or travel patterns of expanded GPS data	Gravity model	Gravity model
Truck trip assignment	Multiclass assignment with separate truck trip tables and appropriate passenger car equivalent (PCE) values	Multiclass assignment with separate truck trip tables and appropriate PCE values	Multiclass assignment with separate truck trip tables and appropriate PCE values	Multiclass assignment with separate truck trip tables and appropriate PCE values

Note: [a] Recommended characteristics are subject to resource constraints such as data availability and budget.

Truck trip tables in MPO models include mainly service trucks. When freight trucks are included, most are internal-external (I-E), external-internal (E-I), and external-external (E-E) truck trips. E-E truck traffic is affected more by an MPO's location relative to major national freight highway corridors than by conditions on the roads in the region. Service (nonfreight) trucks that operate within the region may be the focus for truck models of MPOs.

Since MPO models generally deal only with the truck mode, there is no mode choice function. MPO models therefore deal only with truck trip generation and distribution, with trucks being assigned along with autos during highway assignment.

Some modeling practitioners create a truck trip table by factoring the auto vehicle trip table so that the total truck VMT would meet an aggregate target, say 7 to 10 percent of regional VMT. However, the origins, destinations, and routes chosen by trucks are different than the travel patterns of auto trips. Merely factoring the auto tables may produce the correct cumulative VMT for trucks, but the travel patterns will probably be erroneous. Factoring auto trip tables is therefore **unacceptable practice**.

Trip Generation

The first edition of the QRFM [51] based the estimation of truck productions and attractions on certain socioeconomic data categories:

- Agriculture, Mining and Construction;
- Manufacturing, Transportation, Communications, Utilities, and Wholesale Trade;
- Retail Trade;
- Office and Services; and
- Households.

Table 8.5 presents some examples of truck trip generation equations from *NCHRP Report 606* as well as that from the 1996 QRFM. In this process, the estimated productions and attractions for truck are summed before proceeding to the trip distribution step. However, there is value in retaining the information associated with the purposes represented by these categories. As an example, the Los Angeles MPO developed a truck model [52] that retained truck "purposes" through additional model steps.

Commercial vehicle trip diary surveys are a useful method of data collection, particularly for understanding internal-internal (local) truck trip activity in an urban area. The basic approach of data collection involves selecting a representative sample of trucks operating in the region and obtaining travel diaries from truck drivers for a certain time duration.

The basis for estimating the parameters of the truck trip generation equations is a truck or commercial vehicle survey, or perhaps an establishment survey. However, in many cases a local survey is not available. Transferring truck trip generation parameters from other sources is not an ideal practice; as shown in Table 8.4, even when the same variables are used in truck trip generation for combination trucks, there is considerable variation among different areas in the coefficients of these variables. The amount of truck travel depends on the makeup of the region's economy among service, heavy manufacturing, high-value manufacturing industries, resource extraction, and other industries. Since regional economies differ, it should be expected that the amount of truck travel supporting these economies differ. For that reason, the use of local surveys to establish truck generation rates is preferred. However, it is recognized that in the absence of such surveys, transferred parameters may be required. In such cases, it is essential that the amount of truck travel be validated during the highway assignment validation, using vehicle classification counts and adjusting transferred rates as necessary.

Table 8.4 Combination Internal Truck Trip Rates

Variable	Phoenix (1991)[a]	Washington	Vancouver[b]	San Francisco (1993)[c]	New Jersey Truck Model	Richmond[d]	QRFM (1996)
Retail Employment	0.0615	0.0300		0.0001	0.0590	0.140	1.206
Industrial Employment	0.0833	0.0300	0.0665	0.0293	0.0800	0.25	1.284
Public Employment	0.0400	0.0200		0.0220	0.0384		
Office Employment	0.0053	0.0200	0.1640	0.0220	0.1207	0.029	0.514
Total Employment				0.0112			
Agricultural Employment							1.573
Households	0.0210				0.0202	0.068	0.038

Source: Cambridge Systematics et al., "Forecasting Statewide Freight Toolkit, NCHRP Report 606," 2008 [53]; Cambridge Systematics et al., "Quick Response Freight Manual," 1996 [51].

Note: [a] Trucks over 28,000 pounds – attraction rates only.
[b] Trucks over 44,000 pounds.
[c] Assumed three- and four-axle truck rates are "heavy truck"– production rates only.
[d] Base 2017.

A more recent approach is the use of Geographic Positioning Systems (GPS) receivers, which are used to trace individual truck trip activity. However, GPS-based data collection in itself cannot provide key truck trip characteristics pertaining to commodity hauled, shipment size, and activity at trip end. These GPS data can be used to identify trip ends and compile results into an O-D trip table for trucks. Expansion of the data is critical and not straightforward. When paired with a model, expansion is often performed by a factoring method or an ODME process so that assigned truck volumes more closely resemble truck counts. By utilizing land use and employment data by sector, trip generation of truck trips can be related to the economic development indicators for a region.

It is **acceptable practice** for all regions to transfer truck trip generation parameters and validate them to match the amount of truck travel indicated by vehicle classification counts. It is also **acceptable practice** to develop truck trips by establishing the relationship between the truck GPS data and land use data. It is **recommended practice** in large areas to develop truck trip generation parameters from local survey data.

Some regions may have facilities such as ports, truck terminals, and intermodal facilities, that generate truck traffic that may not be consistent with the trips generated using the employment-based trip rates. If such facilities exist, it is both **acceptable practice** and **recommended practice** to treat these facilities as special generators (see Section 5.1.5). If data for these facilities, including special generator surveys (see Section 4.2.1) and person and vehicle counts are available, they should be used to estimate truck trips.

Trip Distribution

The 1996 edition of the QRFM presents the use of exponential friction factors in a gravity model to distribute truck trips. The recommended formulations use travel time in minutes as the impedance measure and are as follows:

For all light trucks:

$F_{ij} = e^{-0.08} * t_{ij}$ (coefficient corresponds to 12.5-minute average trip length)

For all medium trucks:

$F_{ij} = e^{-0.10} * t_{ij}$ (coefficient corresponds to 10-minute average trip length)

For all heavy trucks:

$F_{ij} = e^{-0.03} * t_{ij}$ (coefficient corresponds to 33.3-minute average trip length)

Where:
F_{ij} = friction factor for O-D pair *ij*, and
t_{ij} = congested travel time for O-D pair *ij*.

The gravity model as formulated may connect purposes that have little reason to be connected (for example, mining truck productions connected to household truck attractions). This may be addressed by modifying the truck trip generation equations so that the propensity to make trips between purposes is also considered. As an example, the Phoenix MPO determined the percentage of trips that were made between TAZs using a GPS survey of trucks and included that information in a modified trip distribution process, as shown in Equation 8-2.

$$T_{ilu_m jlu_n} = PctP_{lu_m lu_n} * P_{ilum} * \frac{PctA_{lu_m lu_n} * A_{jlu_n} * FF_{ij}}{\sum_j PctA_{lu_m lu_n} * A_{jlu_n} * FF_{ij}} \quad (8\text{-}2)$$

Where, as in the gravity model:

$T_{ilu_m lju_n}$ = The number of trips, *T*, between land use activity *m* in TAZ *i* and land use activity *n* in TAZ *j;*

P_{ilu_n} = The productions, *P*, of land use activity *m* in TAZ *i;*

A_{jlu_n} = The attractions, *A*, of land use activity *n* in TAZ *j;*

FF_{ij} = The friction factor of travel between TAZs *i* and *j.*

The nonstandard terms limit the interchanges, which are computed between TAZs, to those that are most likely to occur:

$PctP_{lu_m lu_n}$ = the Percent of Productions, *PctP*, of land use activity *m* that are made to land use activity *n;*

$PctA_{lu_m lu_n}$ = the Percent of Attractions, *PctA*, in land use activity *m* that are made to land use activity *n.*

These percentages between land use activities might be obtained from a commercial vehicle survey or from a GPS survey of trucks.

If local data for estimating a truck model are unavailable, an origin-destination matrix estimation (ODME) process may be used to create truck trip tables. If a truck model distinguishes trucks by type and sufficient truck counts are available, the development of a truck table from an ODME process can serve as the estimation database for the development of truck trip generation equations, the identification of special generators including external stations, and trip distribution equations.

It is **acceptable practice** and **recommended practice** for all regions to use a gravity model formulation for truck trip distribution. It is also **acceptable practice** for all areas to develop truck trip generation and distribution parameters from an ODME process.

Assignment

Trucks should be assigned together with autos and other vehicles in order to account for the interaction of these vehicles on performance. As noted in the discussion of freight assignment, truck restrictions or preferences on links should be considered in the assignment rules. Additionally, if capacity is stated in passenger cars per hour, a passenger car equivalent (PCE) should be used to factor the truck trip table. A combination truck on the relatively flat terrain associated with most MPO models is typically equivalent to 1.5 to 2.0 autos. It should be noted that this PCE includes not only a comparison of the physical lengths of the vehicles, but also the effective lengths of the vehicles, including their safe stopping distance. As an example, the Indiana DOT has studied PCEs for trucks and recommend PCE values for single-unit and combination truck for basic urban freeways (level terrain) of 1.35 and 1.60, respectively [54].

It is **acceptable practice** and **recommended practice** for all regions to use a multiclass assignment with separate truck trip tables and appropriate PCE values for truck trip assignment.

8.3 Truck Model Validation

8.3.1 Data Sources for Validation

A variety of data sources can be obtained to validate truck/freight models. These are discussed in the subsections that follow.

Vehicle Registration Data

Truck registration data multiplied by average trips per day per truck can provide a total regional control total of truck trips, potentially by purpose. State vehicle registration databases often indicate whether registered vehicles are used for commercial purposes. It should be recognized, however, that motor carriers and private fleet operators may register their trucks in states based not on operations but on consideration of state taxes and regulations and adjustments. State truck registrations may therefore underestimate or overestimate the actual size of a state's active truck fleet. Vehicle data also may be purchased from R.L. Polk & Co., a privately-owned consumer marketing information company.

Commercial Vehicle Surveys

Commercial vehicle surveys can serve as a data source not only for estimating truck trip generation and distribution model parameters, but also for validating model results. If a commercial vehicle survey is used to develop a service truck model, and the service truck model will be used together with a freight model (even if only for external trips), an effort should be made to remove the freight trucks from the estimation database to avoid "double counting" of these trucks.

Vehicle Classification Counts

Section 4.2.3 discusses traffic count data. Vehicle classification count data, which classifies vehicles according to the 13 axle-based classes defined by FHWA, are generally available from VDOT for sampled highways. For the 13 classes, the information includes counts by location, hour of the day, and date. In summary format, this information generally presents truck volumes (defined as FHWA Classes 5 through 13, six tires and above) and occasionally includes buses (FHWA Class 4). Four-tire pickup trucks, vans, and sport utility vehicles (FHWA Class 3), are almost always included with passenger cars.

Commodity Flow Data

There are several public and private sources for freight origin-destination data in the United States. The most commonly used sources include the following:

- TRANSEARCH (annual freight tons by STCC commodity and mode between user-defined zones). TRANSEARCH is a privately maintained comprehensive market research database for intercity freight flows complied by IHS Markit.

- FHWA Freight Analysis Framework (annual freight tons by STCG2 commodity and mode between 132 FHWA-defined zones). The FAF is based entirely on public data sources and transparent methods and has been expanded to cover all modes and significant sources of shipments.

- U.S. Census Bureau and Bureau of Transportation Statistics (BTS) Commodity Flow Survey (CFS) (annual freight tons by STCG2 commodity and mode for origin and destination Metropolitan Statistical Areas). The CFS is developed through a partnership between the Research and Innovative Technology Administration (RITA), Bureau of Transportation Statistics (BTS), and the U.S. Census Bureau, U.S. Department of Commerce. This survey provides data on the movement of goods in the U.S., including information on commodities shipped, value, weight, and mode of transportation as well as origins and destinations of shipments of manufacturing, mining, wholesale, and selected retail establishments.

- Surface Transportation Board's Carload Waybill Sample (annual freight tons by STCC commodity by rail between U.S. Bureau of Economic Analysis (BEA) Economic Areas (public release) and U.S. Counties (restricted release) and intermediate rail junctions). The Waybill Sample is a stratified sample of carload waybills for terminated shipments by rail carriers. A waybill is a document issued by a carrier giving details and instructions relating to the shipment of a consignment of goods. Typically, it will show the names of the consignor and consignee, point of origin of the consignment, destination, route, method of shipment, and amount charged for carriage.

- U.S. Army Corps of Engineers' Waterborne Commerce Statistics Database (annual freight tons by Harmonized Series (HS) commodity by water for U.S. ports and waterways). The Waterborne Commerce Statistics Database presents detailed data on the movements of vessels and commodities at the ports and harbors and on the waterways and canals of the United States and its territories. Statistics are aggregated by region, state, port, and waterway for comparative purposes. Data on foreign commerce are supplied to the USACE by the U.S. Bureau of the Census, U.S. Customs, and purchased from the Journal of Commerce, Port Import Export Reporting Service.

- U.S. Census Bureau's Vehicle Inventory and Use Survey (VIUS) (truck miles and ton-miles, by VIUS commodity groups, by truck type). The VIUS provides data on the physical and operational characteristics of the nation's truck population. Its primary goal is to produce national- and state-level estimates of the total number of trucks. The first survey was conducted in 1963. It was then conducted every five years beginning in 1967 and continuing to 2002. Prior to 1997, the survey was known as the Truck Inventory and Use Survey (TIUS). VIUS has not been collected as part of the Economic Census since 2002.

8.3.2 Validation Checks

The validation checks for truck models include checks of truck trip generation, trip distribution, and assignment, and are similar to the checks for the corresponding passenger model components.

Trip Generation

As discussed in Section 5.2.2, aggregate trip generation checks focus on comparisons of modeled trip ends to observed data. In the case of truck models, the observed data would be from a commercial vehicle survey (or perhaps an establishment survey) if such a survey data set is available. There are no specific guidelines for how close the match should be since these survey data sets generally have a lot of variation in trip rates, and a better check of the amount of truck travel comes from the comparison of assigned truck volumes to truck counts (see below).

Truck Trip Distribution

As discussed in Section 6.2.2, trip distribution checks focus on comparisons of modeled trip lengths and origin-destination patterns to observed data, again from a commercial vehicle or establishment survey if available. The same types of checks (comparisons of average trip lengths by truck type, coincidence ratio, etc.) used for person trip distribution model checks can be performed. As with truck trip generation checks, there are no specific guidelines for how close the match should be.

Assignment

After assignments of vehicles by type (automobile and truck at a minimum), the vehicle classification counts can be used to compare the observed automobile and truck counts (and shares by vehicle type) with the estimated automobile and truck volumes (and shares) produced by the travel demand model. These vehicle assignments will include both personal and commercial vehicles, derived from both personal and commercial models, and so calibration adjustments deemed necessary from these comparisons may be required for either the personal or commercial models or both. The validation summaries are also usually summarized by functional class, area type, and screenlines. Chapter 10 provides more information on traffic assignment validation.

Highway assignment validation must consider all trucks. The link flows of trucks include both freight truck and service trucks. If a model estimates these flows separately, each of their volumes should always be less than the total observed flows. There are several classification systems for trucks used within the U.S. DOT. The BTS in the (now discontinued) VIUS uses a system of eight weight-based classification for trucks, which was adopted by the EPA and other agencies. FHWA uses a system of 13 axle and body types that is used by state DOTs and others for vehicle classification counts. Additionally, very light trucks – those with only four tires, such as pick-up trucks – also are widely used for personal travel while their volumes are reported as combined. If a truck model is based on one classification system and the validation data uses another classification system, adjustments should be made before using the validation data.

When trucks are assigned with autos using multiclass assignment, parameters should be checked to ensure that they have been modified as necessary to accommodate trucks. These parameters include equilibrium convergence criteria (number of iterations, relative gap, etc.), volume-delay function parameters, time-of-day factors, and PCE factors.

8.3.3 Model Calibration and Troubleshooting

Since truck trip assignment is performed as part of the overall highway assignment process that includes passenger cars, the validation and calibration process is not completely separable from the process for highway assignment described in Section 10.5. The assigned truck volumes by type should be compared to the corresponding vehicle classification counts (e.g., modeled heavy truck volumes should be compared to heavy truck counts). Since changes to network and assignment parameters affect both auto and truck assignment results, changes should not be made only to address truck model validation concerns.

If truck volumes are generally too high or too low while auto volumes are not, this is likely a reflection of issues with the truck trip tables and therefore the truck trip generation and distribution processes. This is especially true if those model components used transferred parameters rather than locally estimated parameters. It therefore makes sense to consider adjusting the parameters of these models to address general overassignment or underassignment. For example, if truck volumes are generally too high, truck trip rates can be reduced, or friction factors in the trip distribution model adjusted to reduce the average truck trip length. These types of revisions can be made for specific truck types as indicated by the comparison of modeled volumes to counts by truck type.

If modeled truck volumes (but not auto volumes) are substantially different than counts in localized areas, it may make sense to check, in the vicinity of the issue, the network parameters related to trucks (for example, roadways with truck restrictions) and/or volumes for large generators of truck trips in the vicinity.

CHAPTER 9. MODE CHOICE

This chapter pertains to those regions in Virginia where transit is modeled, and therefore mode choice must be considered. As discussed in Section 1.4, Virginia includes large model regions where it is required that transit travel be explicitly modeled, smaller regions where transit needs to be modeled (for use in planning of transit operations or improvements or to test the potential mode shifting effects of policies and projects being considered), and smaller regions where it is not necessary or efficient to model transit.

Mode choice is the third step in the four-step modeling process and is performed only in models where transit travel is considered. In this step, the person trip tables created in the trip distribution step are split into trip tables by travel mode. The travel mode definitions vary by region and are discussed further in Section 9.1.2.

The main inputs to mode choice models include the trip distribution outputs – the production TAZ to attraction TAZ person trip tables by trip purpose – and measures of travel time, cost, and other level of service variables between each pair of TAZs, obtained (skimmed) from the transportation networks. Socioeconomic and area characteristics are sometimes also used as inputs. The outputs of mode choice are production TAZ to attraction TAZ trip tables by mode for each trip purpose. Because trips of different purposes have different levels of sensitivity to travel time and cost, mode choice is applied separately for each trip purpose, with different model parameters.

This chapter describes the policies and procedures for developing, validating, and calibrating mode choice models in Virginia.

9.1 Mode Choice Practice

The policies and procedures for mode choice practice in Virginia are summarized in Table 9.1.

Table 9.1 Mode Choice Modeling Practice for Virginia Travel Demand Models

Component	Acceptable		Recommended	
	Small[a]	Large	Small[a]	Large
Model form	Nested or multinomial logit	Nested or multinomial logit	Nested or multinomial logit	Nested logit
Modes	Auto, transit	Auto, transit	Auto, transit	Auto: SOV, HOV[b] Transit: Walk access, auto access
Level of service variables	In-vehicle travel time (IVTT), out-of-vehicle travel time (OVTT), cost	IVTT, OVTT, cost	IVTT, OVTT, cost	IVTT, OVTT, cost, transfers if determined to be significant
Other variables	As needed		As needed	

Note: [a] Only if nonauto modes are included in the model (see Chapter 5).

[b] If HOV facilities/policies are important in the region.

9.1.1 Model Form

The **logit model** is the most common type of mode choice model. For more information about logit models, a good summary is provided in Section 4.1 of *NCHRP Report 716*. For more detailed information, other good sources include Ben-Akiva and Lerman (1985) [55] and Koppelman and Bhat (2006) [56].

The logit model is an example of a discrete choice model. Discrete choice analysis uses the principle of utility maximization. A decision-maker is modeled as selecting the alternative with the highest utility among those available at the time a choice is made. An operational model consists of parameterized utility functions for the choice alternatives in terms of observable independent variables and unknown parameters.

The utility represents the individual's value for each choice alternative, and its numerical value depends on attributes of the available options and the individual. An analyst never knows the true utility function, because of variables that are not included in the data set, that the analyst chooses to omit from the model (e.g., because he cannot forecast them well), or that are completely unknown to the analyst. The model estimates the probability that each alternative is chosen by an individual in a particular segment of the population, defined by geography (origin-destination of trip) and personal characteristics.

The simplest function used in mode choice models is the multinomial logit formulation. In this type of model, the probability of each alternative is expressed as shown in Equation 9-1.

$$P_i = \frac{\exp(V_i)}{\sum_j \exp(V_j)} \qquad (9\text{-}1)$$

where:

P_i = Probability of choosing alternative i

V_i = Utility (deterministic) of alternative i

The probabilistic nature of the choice reflects that the true nature of the complete utility function is unknown; the true utility includes variables not included in the deterministic component of utility V_i. The form of the utility functions is shown in Equation 9-2.

$$V_i = B_{i0} + \sum_k B_{ik}\, x_k \qquad (9\text{-}2)$$

where:

B_{i0} = The constant associated with alternative i

B_{ik} = The coefficient indicating the relative importance of variable k on choice i

x_k = The value of decision variable k

Another logit model form that is often used for mode choice is the **nested logit model**. Under a nested structure, the model pools together choice alternatives that share similarities, and the choice is represented as a multistep decision. The probability of choosing an alternative within its nest of similar alternatives is given by the multinomial logit formula (Equation 9-1). The probability of choosing a nest of alternatives among other nests at the same level also is given by Equation 9-1, where the nest utilities are composite utilities of the alternatives in the nest, computed using a logsum variable representing the expected maximum utility of the set of alternatives in the nest. The logsum is computed as the logarithm of the denominator of the multinomial logit mode choice probability function for the alternatives within the nest. Figure 9.1 depicts the multinomial and nested logit model structures.

In models with a mode choice component, the use of either a multinomial or nested logit model is considered **acceptable practice** in all regions. If there are more than two alternatives, the use of a nested logit model is considered **recommended practice**.

Figure 9.1 Multinomial and Nested Logit Models

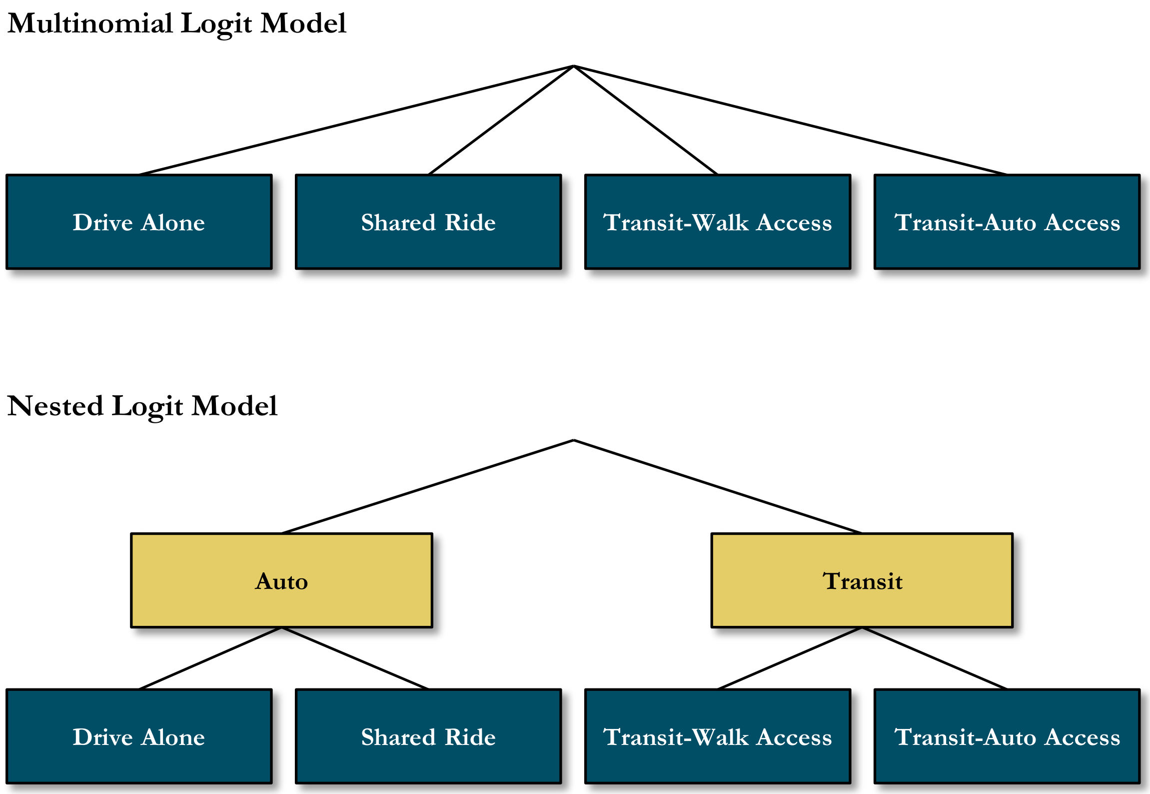
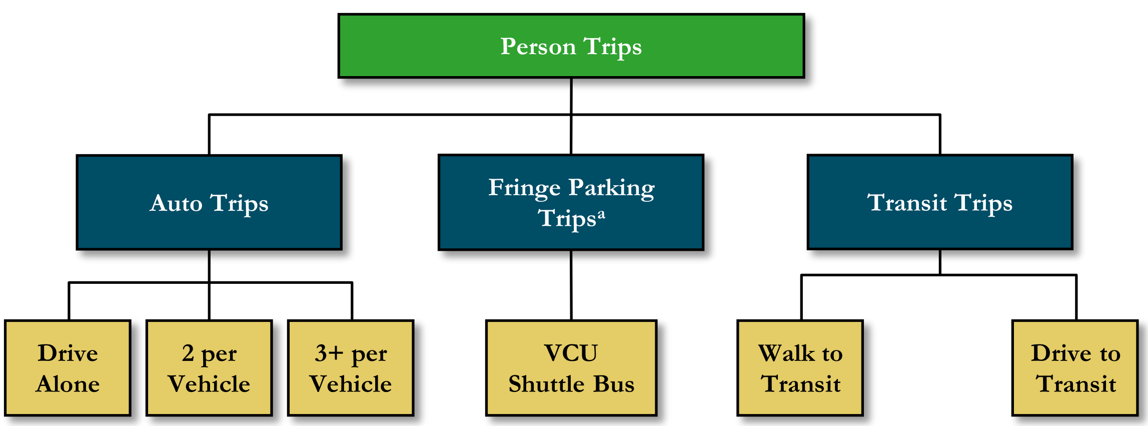


Figure 9.2 presents an example mode choice model from the RTC Model, Base 2017 [40]. The model has six modes in three nests, including a separate mode for the Virginia Commonwealth University Shuttle Bus. Table 9.2 presents the coefficients (i.e., the B_{ik} from Equation 9-2) for the variables in the mode choice model.

Figure 9.2 RTC Mode Choice Model Nest Structure (Base 2017)



[a] *For HBW and HBO purpose only.*

Table 9.2 RTC Mode Choice Model Coefficients (Base 2017)

Parameters	Values	Equivalent IVTT
Level of Service Variables		
In-vehicle time (minutes)	-0.0250	1.00
Out-of-vehicle time (minutes)	-0.0500	2.00
Cost (cents)	-0.0015	0.06
Number of transfers	-0.1250	5.00
Nesting Coefficients		
Auto/transit	0.5	
Walk/drive/fringe to transit nest	1.0	
Other parameters		
Auto operating cost	10.5 cents per mile	
Shared-ride 2 average occupancy	2.0 passengers	
Shared-ride 3 average occupancy	3.2 passengers	
Auto parking cost	Defined at zone	
Value of time	$10.00 per hour	

Source: Adapted from AECOM, "Richmond / Tri-Cities Model Update Technical Memorandum," 35, Table 6.1, 2020 [40].

Note: Mode choice model constants for the RTC model are split into three market segments based on the destination location – Downtown Richmond, Downtown Petersburg, and rest of the model region. Mode specific constants are developed for all purposes and time periods by market segment.

9.1.2 Modes

For regions using a mode choice model, it is **acceptable practice** to include only two travel modes, representing automobile and transit. It is **recommended practice** to include additional travel modes. Auto can be segmented into single-occupant vehicles (SOV) and high-occupancy vehicle (HOV), with HOV possibly being segmented into two-occupant and three (or more)-occupant vehicles if policies or investments that treat these vehicle occupancy classes separately are being considered in the region. In regions with significant travel by transit with auto access, transit should be segmented by auto access and walk access, with auto access potentially segmented by park-and-ride and kiss-and-ride (dropoff/pickup) if there is significant travel by each access mode. Transit may be further segmented by type of transit, such as local bus, express bus, commuter rail, light rail, and subway/elevated if these modes exist in the region. However, this additional segmentation should be considered only if these submodes truly compete with one another in the same geographic areas. There are costs and complexity associated with including more modes in the models. An alternative approach to distinguishing different transit modes is to incorporate their distinct charateristics in the transit assingment and pathbuilding process.

If nonmotorized travel is carried through earlier model steps, at least a single nonmotorized mode is included in mode choice. The nonmotorized mode may be further segmented into walk and bicycle if there is significant bicycle travel in the region and sufficient data are available to estimate and validate the model for these modes.

9.1.3 Level of Service Variables

The variables in the mode choice model utility function (x_k in Equation 9-2) are primarily *level of service variables* that describe and distinguish the service experienced by travelers on each mode. Most of these variables reflect measures of travel time and cost, although some (such as transit transfers) reflect other service characteristics.

The following level of service variables should be included in all models:

- **In-vehicle travel time** (IVTT) **–** The time spent traveling inside vehicles (autos or transit vehicles);
- **Out-of-vehicle travel time** (OVTT) **–** The time spent walking or bicycling to or from the main travel mode at both ends of the trip, transferring between vehicles, or waiting for transit vehicles; and
- **Cost –** The cost associated with travel, including auto operating costs, parking costs, tolls, and transit fares.

It is **acceptable practice** for all regions to include these three (aggregate) level of service variables in mode choice models. The individual variables are computed as TAZ to TAZ matrices through "skimming" the highway and transit networks using the modeling software.

It is **recommended practice** for all regions to consider additional level of service variables. These may include nontime/cost variables such as the number of transit transfers or segmentation of the three main variables. For example, OVTT may be separated into wait time, walk access/egress time, and/or transfer time. Cost may be segmented by type (auto operating, parking, tolls, and transit fares).

9.1.4 Other Variables

It is considered both **acceptable practice** and **recommended practice** for all model regions to use only level of service variables in mode choice models. However, other variables may be considered. These may include characteristics of the traveler or his household, such as income level or vehicle availability. Such variables may be used directly in the utility functions or may be used to segment the travel markets.

9.1.5 FTA Considerations in Mode Choice Model Development

Current Federal Transit Administration (FTA) guidance allows project sponsors to choose among three different approaches to prepare ridership forecasts, as discussed in Section 1.2.3. Thus, FTA recognizes that there are no standard or "correct" methods that are universally applicable to all regions. Mode choice models will need to reflect the fact that each metropolitan area has unique conditions and must be responsive to local decision making. If the models are used to forecast transit ridership, it is essential that they explain the current transit conditions and capture the tradeoffs between travel times and costs as well as fulfill their ultimate objective of yielding reasonable forecasts. These favorable properties are heavily dependent on the model calibration and validation procedures with rigorous quality assurance checks that are described in this chapter.

During review of forecasts that may support New Starts/Small Starts applications, FTA considers the five key aspects of travel forecasts for project evaluation, as discussed in Section 1.2.3. As part of this review, FTA looks for potential problems in mode choice models in "local" models. Some examples include: unusual coefficients in mode choice models, bizarre alternative-specific constants, and inconsistencies between path parameters (see Section 10.4 for discussion on transit path building) and mode choice coefficients. Since these problems can have a cascading effect of producing errors in trips, FTA suggests that modelers ask themselves if patterns across market segments are explainable. FTA also suggests that there be conformity between parameters used in transit path selection and mode choice utility expressions for transit choices. That is, the path building process must weigh the various travel time and cost components in a manner that is consistent with the relative values of the mode choice coefficients.

If a travel forecasting model is going to be used to produce forecasts to support a New Starts or Small Starts application, FTA encourages early and regular communication with their travel forecasting staff during mode choice model development, even if it is independent of a specific transit project.

More information can be found at https://www.transit.dot.gov/funding/grant-programs/capital-investments/travel-forecasts.

9.2 Mode Choice Validation

The mode choice model validation process is connected with the transit path building and assignment validation processes, which are described in Sections 10.4 and 10.6, respectively. Any calibration of the transit assignment process may lead to model changes that affect mode choice, whether they are network changes, revisions to path building or skimming, or other changes to the model. The mode choice models cannot be considered completely validated until the transit path building and assignment models also have been validated.

9.2.1 Data Sources for Validation

The main sources of data for validation of mode choice models include the following:

- **Transit ridership counts** have the best information on the total amount of travel by transit, usually at the route level. It is important to recognize, however, that ridership (boarding) counts represent "unlinked trips," meaning that a person is counted each time he or she boards a new transit vehicle. So a trip that involves transit transfers is counted multiple times. Mode choice models consider "linked trips," where a trip including transfers counts as only a single trip. Information on transfer rates is required to convert unlinked trips to linked trips; such information generally is obtained from transit on-board surveys.
- **Transit rider survey –** A transit rider survey (typically an on-board survey) is an invaluable source of information for validation of the transit outputs of mode choice models. A wealth of information that cannot be obtained from transit counts is available from on-board surveys, including:
  - Transit trip origin-destination patterns by trip purpose;
  - Access modes;
  - Transit paths (ideally, surveys should ask riders to list all routes used in order in the path for the linked trip);
  - Transit submodes used (e.g., bus, light rail);
  - Transit transfer activity; and
  - Characteristics of the surveyed riders and their households.
- **Household travel/activity survey –** For modeling in Virginia, the National Household Travel Survey (NHTS) Add On records are considered household surveys. The household survey is the best source for information on nontransit travel data since the number of observations for transit travel is usually small. The expanded household survey data can be used to produce observed mode shares for nontransit travel by purpose for a number of geographic and demographic market segments.
- **Census data –** The Census Transportation Planning Products (CTPP) contain information on modes for work travel. The Census Bureau uses the American Community Survey (ACS), which is conducted continuously, to collect data on work location and travel (among other items). Section 6.2.1 discusses how work travel is treated differently in the ACS compared to travel models.
- **National sources –** National data sources include the National Household Travel Survey (NHTS), *NCHRP Report 716*, and other documents (e.g., *TCRP Report 73, Characteristics of Urban Travel Demand*).

9.2.2 Validation Checks

Table 9.3 summarizes the model validation checks for mode choice models.

Table 9.3 Mode Choice Validation Procedures for Virginia Travel Demand Models

Type of Check	Model Region Size	
	Small	**Large**
Check parameter estimates	Reasonableness check only	Reasonableness check only
Compare modeled trips by mode (mode shares) to observed data by market segment	Reasonableness check only	Reasonableness check only
Check modeled vehicle occupancy (if auto submodes are included)	Reasonableness check only	Reasonableness check only
Compare modeled transit trip lengths to observed data	Reasonableness check only	Reasonableness check only
Checks of model sensitivity to input variables	Reasonableness check only	Reasonableness check only

Check Parameter Estimates for Reasonableness

Mode choice model parameters, the coefficients and constants in the utility functions, may be estimated using local data, transferred from another model, or asserted. An important check is that all mode choice model parameters should be of reasonable sign and magnitude. Estimated parameters should be checked not only for reasonableness, but also for statistical significance. A complete set of statistical tests should be performed as part of the model estimation process.

The determination of "reasonable" requires experience and judgment. One common way of examining reasonableness is to compare the magnitude of model coefficients to those used in other models. Some of the national resources, including *NCHRP Report 716* and the FHWA Validation Manual, include examples of model parameters from areas around the U.S.

The values of model parameters, however, depend on model structure, the presence or absence of other variables, and the context of the area being modeled. It is not valid, for example, to assume that the coefficients in a model with three variables would be the same as the coefficients for the same variables in a model with those same three variables plus two others. It also would be unreasonable to assume that, for example, a cost variable coefficient in a model, which represents the sensitivity of mode choice to, say, one dollar of travel cost, would be the same in another model for an area with a significantly higher cost of living, or even in another model estimated for the same area 5 or 10 years earlier.

Level of service coefficients should always be negative in sign since higher values of the variables (time, cost) for a mode represent a worse level of service. These coefficients represent the sensitivity of mode choice to particular components of level of service. Therefore, they might be expected to have similar values for all mode choice models, at least those structured similarly, since it would seem unlikely that travelers in one urban area are far more or less sensitive to, say, wait time than they are in another area.

It is important to consider the coefficients not only individually, but also the relationships between them. In nearly all mode choice models, coefficients for variables representing out-of-vehicle time – including wait, walk access/egress, and transfer time – are greater in absolute value than in-vehicle time coefficients. This relationship implies that time spent waiting or walking is considered more onerous than time spent in a vehicle, usually sitting (see Table 9.2). Typically, the ratios of out-of-vehicle time coefficients to in-vehicle time coefficients are about 2 to 3 for home-based work trips with some higher values estimated for nonwork trips.

Another relationship that can be checked is the value of (in-vehicle) time, which is represented by the ratio of the in-vehicle time coefficient to the cost coefficient. Represented in dollars per hour, the values of time is closely related to the traveler's earnings or household income and trip purposes, typically ranging from about $3 to $10 per hour for work trips, with lower values typical for nonwork trips.

If a nested logit mode choice formulation is used, a logsum variable is included in the model specification for each nest of modal alternatives. The coefficients of these variables are estimated or asserted. While there are no specific reasonableness checks of logsum variable coefficients, especially asserted coefficients, the coefficients' validity must be checked with respect to two rules:

- Logsum coefficients must be between zero and one. The coefficients should be statistically different from both zero and one (although statistical significance can be checked only for estimated coefficients, not for asserted coefficients).
- The logsum coefficient for a nest should be lower than the logsum coefficient for any higher level nest of which the nest is a component.

Mode-specific constants also are model parameters that should be checked for reasonableness. Checks of constants are discussed in Section 9.2.3.

Comparison of Modeled Trips to Observed Data

The most basic aggregate checks of mode choice model results are comparisons of modeled trips by mode, or mode shares, to observed data by market segment. Market segments include trip purposes as well as demographic segments, such as income or vehicle availability levels, and geographically defined segments.

Mode choice models are applied using person trip tables as inputs. The mode choice model's results, therefore, represent shares of the total trip table that use each of the mode choice alternatives. Validation of the model's aggregate results involves checking the shares for the model's base-year scenario results against observed mode shares.

A household survey is the only comprehensive data source covering all modes, and therefore is the only source for mode shares. However, shares for modes that are used relatively infrequently – notably transit modes – as well as mode shares for relatively small segments of the population (for example, zero-vehicle, high-income households) cannot be accurately estimated from household surveys due to small sample sizes. While it may be problematic to find an alternate source for some segments or modes (such as bicycle travel), transit trips and shares by segment may be estimated using other data sources, including ridership counts and transit rider surveys.

Transit ridership counts provide estimates of total transit trips, not mode shares. To convert these trips to shares, an estimate of the total trip table for each market segment is needed. Assuming good validation of the trip generation and distribution components, the trip table outputs from the trip distribution model can provide this information. Basically, the transit trips by submode, access mode, trip purpose, and other segmentation level, segmented using the transit rider survey data (and converted from unlinked trips to linked trips), can be subtracted from the total trips represented in the trip distribution outputs to obtain estimates of "observed" nontransit trips. The nontransit trips can be separated into trips by individual mode (auto and nonmotorized submodes) using information from the household travel survey.

Check Modeled Vehicle Occupancy

Checks of vehicle occupancy are performed when the mode choice model includes more than one auto submode (for example, SOV and HOV). In such cases, the split between the auto submodes, which represent vehicle occupancy levels, must be checked. (If only one auto mode is included in the mode choice model, vehicle occupancy factors are used to convert the auto person trips from the mode choice outputs to auto vehicle trips for use in highway assignment.)

The most basic check is to compare the modeled base-year model shares of trips made by vehicle occupancy, both by trip purpose and for all trips, to observed shares. When a sufficient household survey data set is not available, modeled occupancy levels may be compared to representative data from another data set, such as the NHTS, CTPP, or *NCHRP Report 716*. In many cases, the national observed data sources do not represent observed data for the modeled area, and so a precise match is not necessary. The comparison represents more of a reasonableness check.

Comparisons of Modeled Transit Trip Lengths to Observed Data

If observed data on transit trip lengths are available, modeled transit trip lengths should be compared to the observed data. While this is a check of both trip distribution and mode choice, the mode choice model must be run before this check can be performed.

Data on transit trip lengths is usually obtained from transit rider surveys. There are two levels at which observed transit trip length data may be available:

- For the in-vehicle portion of transit trips (stop to stop); and
- For entire trips (origin to destination).

Modeled trip lengths can be obtained for either level although the analyst should be careful to ensure that the model results are on a consistent basis with the observed data. For example, a commuter rail survey yields data on the average length of trips on commuter rail. In this case, for modeled trips that include both commuter rail and bus segments, the length of the commuter rail segment must be considered when comparing to the observed data.

At either level, it is worthwhile for transit trip length comparisons to be segmented using available variables. If the survey data source can provide statistically significant information on trip lengths by trip purpose, traveler/household characteristics (e.g., income level), or subregional geography, it makes sense to perform the comparisons by market segment.

Sensitivity Testing

Sensitivity testing can be performed for mode choice models by varying model inputs and checking results for reasonableness. Model inputs that can be varied include level of service variables (time/speed and cost) and any demographic or TAZ level variables that are used as model inputs. Some example tests include:

- Increasing or decreasing highway or transit travel times by a fixed percentage regionwide;
- Increasing/decreasing parking costs in the CBD by a fixed percentage;
- Increasing/decreasing automobile operating costs (e.g., fuel cost in real terms) by a fixed percentage;
- Increasing/decreasing headways on selected transit routes or submodes by a fixed percentage or amount;
- Increasing/decreasing fares on selected transit submodes by a fixed percentage;
- Changing development patterns for forecast years by moving projected new activity among different parts of the modeled region (e.g., from suburbs to small urban centers or from outlying areas to infill); and
- Reallocating the number of households by income level for a forecast year.

The resultant changes in demand due to changes in a model input variable reflect the sensitivity to the variable; the sensitivity level is determined by the coefficient of the variable in the utility function. Simple "parametric" sensitivity tests can be performed by introducing small changes in the input variable or in the parameter itself and checking the results for reasonableness. It can be important to consider that for certain input parameters, the original calibration data for a regional model may include only a narrow range of experienced values (e.g., automobile operating cost per mile). For these parameters in particular, care should be taken in interpreting the outputs of sensitivity tests, particularly when large changes are specified in the input parameters.

The changes in demand for a modal alternative (or group of alternatives) with respect to a change in a particular variable can be expressed as arc elasticities. While there are some rules of thumb for what constitute reasonable elasticities, there are no specifically defined ranges of reasonable elasticities. Generally, experience has shown that elasticities of transit demand with respect to level of service variables are usually well under 1.0 in absolute value. According to work performed as part of the Traveler Response to Transportation System Changes series [57], the Simpson & Curtin formula indicates that the midpoint arc elasticity of transit demand with respect to fare is about –0.4.[8] It is important to recognize that since the logit formulation is nonlinear, the elasticities of modal demand are not constant. The elasticity calculated for one particular "point" (say, a specific market segment defined geographically, demographically, and temporally) will not be equal to the elasticities computed at other points.

9.2.3 Model Calibration and Troubleshooting

Issues discovered during the model checks described in Section 9.2.2 may imply errors in mode choice model parameters, input data (networks/skims or trip tables), or highway or transit path building procedures. Some of the typical problems that may be evident from these tests include the following:

- Transit demand for specific market segments is too high or low: Check trip distribution to determine if the overall travel in the market is correct, check implied transit share for the market, recheck transit skim data related to the market, consider revisions to the logit model structure, consider adding or removing indicator variables related to the market, consider revisions to mode-specific constants (see discussion below).
- Nonmotorized mode shares for specific market segments are too high or low: Check trip distribution to determine if overall travel in the market is correct, recheck skim data (usually distance skims) related to the market, consider adding or removing indicator variables related to the market or adjusting the coefficients of existing indicator variables, consider revisions to mode-specific constants (see discussion below).
- Modeled vehicle occupancy by trip purpose differs significantly from observed levels: Check observed data for errors, check sensitivity to mode choice model input variables and consider adjusting logit model parameters, consider adding or removing indicator variables related to the market or adjusting the coefficients of existing indicator variables, consider revisions to mode-specific constants (see discussion below).
- Auto submode shares for specific market segments are too high or low: Check trip distribution to determine if overall travel in the market is correct, check implied mode share for the market, recheck skim data related to the market, consider adding or removing indicator variables related to the market or adjusting the coefficients of existing indicator variables, consider revisions to mode-specific constants (see discussion below).

[8] The "Simpson-Curtin Rule," a commonly cited guide, is evolved from simplified use of a formula that describes a shrinkage ratio relationship, not an elasticity relationship, as is explained in TCRP Report 95.

- Model too sensitive or insensitive to changes in level of service: Adjust parameters for appropriate level of service variables in utility functions.

Mode-Specific Constants

The interpretation of a mode-specific constant is that it represents the part of the modal utility that is not considered by the variables in the utility function. The variables represent measurable characteristics of the trip, the traveler, and the area on which the trip is made that affect the choice of mode. The constant, therefore, represents the sum of items that affect the choice that are not included in the variables. These items may include reliability, comfort, convenience, safety, and many other factors.

In model estimation, the original values of constants are estimated. The constants can easily be revised so that modeled mode shares match targets. It is evident that the "correct" values for modal constants are unknown since they represent factors affecting choice that could not be quantified sufficiently to be included in other mode variables. It would be incorrect, however, to assume that all validation issues are the result of these unknown factors. As is the case with K-factors in trip distribution (discussed in Section 6.2.3), simple adjustments to modal constants estimated using weighted samples should be considered "a last resort" after all other possible causes for error and calibration adjustments have been considered, and so this is why they are listed as the last items in each bullet above. Because constants can be revised to provide nearly perfect matches between modeled and observed mode shares, it can be very tempting to revise modal constants to resolve differences in shares without determining whether it is the best method to solve the problem at hand.

The values of mode-specific constants, whether estimated or revised during calibration, should be checked for reasonableness. One way of doing this is to compare the value of a constant relative to the constants of other modal alternatives to the values of other parameters. For example, the difference between the rail and bus constants could be divided by the in-vehicle time coefficient to express the difference in units of minutes of "equivalent" in-vehicle time. If the difference between two constants was –0.5 (with the rail constant higher), and the in-vehicle time coefficient was the same for the two modes and equal to -0.025, the difference in the constants is equivalent to –0.5/–0.025 = 20 minutes of in-vehicle time. This implies that all other things being equal, a traveler would be indifferent between a bus trip and a rail trip that is 20 minutes longer.

The interpretation of differences between constants can be muddied somewhat by modal availability issues. For example, it is common to see transit constants that are so much lower than auto constants that it is implied that a traveler would be indifferent between a transit trip and an auto trip that is several hours longer. However, many travelers may not have the auto mode available while others do not consider transit as a viable mode.

CHAPTER 10. TRIP ASSIGNMENT

Trip assignment is the fourth and final step of the four-step modeling process. It includes:

- **Highway assignment**, in which the routes of auto and truck vehicle trips along the highway network are estimated; and
- **Transit assignment**, in which the routes of person trips along the transit network are estimated. Transit assignment is performed only in models where transit travel is considered.

This chapter describes the policies and procedures for developing, validating, and calibrating highway and transit assignment models in Virginia. It also covers the related topic of highway and transit "**network skimming**." The skimming process entails creating TAZ to TAZ matrices of level of service (time and cost) variables using the optimal paths between TAZs. These matrices are key inputs into the trip distribution and mode choice processes. The relationship between network assignment and skimming is that both involve building optimal paths between TAZs. The assignment process uses these paths to load the highway vehicle and transit person trip tables onto the network to obtain roadway volumes and transit boardings and volumes. The skimming process uses the paths to develop the matrices of level of service variables.

This chapter is organized as follows. Section 10.1 discusses highway assignment while Section 10.2 presents the procedures for transit assignment. Section 10.3 describes highway network skimming while Section 10.4 discusses transit network skimming. The process of highway assignment validation is described in Section 10.5 while Section 10.6 discusses transit assignment validation.

10.1 Highway Assignment Practice

The policies and procedures for highway assignment practice in Virginia are summarized in Table 10.1.

Table 10.1 Highway Assignment Practice for Virginia Travel Demand Models

Component	Acceptable		Recommended	
	Small	Large	Small	Large
Assignment algorithm	Any multipath method	Equilibrium assignment	Equilibrium assignment	Equilibrium assignment
Time periods modeled	Daily	Daily; AM, PM, and off-peak	Daily; AM, PM, and off-peak	Daily; AM, PM, midday, and night
Speed-volume relationship	BPR, conical, or Akcelik function		BPR, conical, or Akcelik function	

The main inputs to highway assignment include the highway network, as described within Section 4.1.3, and the vehicle trip tables. The vehicle trip tables may include:

- **Internal auto vehicle trip tables**, which are outputs of the mode choice model (see Chapter 9), or the trip distribution model (see Chapter 6) if a three-step process is used;
- **External vehicle trips** (see Chapter 7); and
- **Truck trip tables** (see Chapter 8).

The internal auto vehicle trip tables may include separate tables for single occupant vehicles (SOV) and high-occupancy vehicles (HOV) if these modes are distinguished in the mode choice model (see Section 9.1.2). It is usual practice to model SOV, HOV, and trucks as separate vehicle classes through a multiclass assignment procedure, which is readily implementable in the modeling software.

Highway assignment determines vehicle routing from origin to destination along shortest paths along the network, with consideration of the effects of congestion on travel time. This is done through **volume-delay functions**, which include parameters relating travel time to volume and capacity. All vehicle trip tables are assigned together in a process known as **equilibrium assignment**.

10.1.1 Assignment Algorithm

Although there has been considerable progress made in the development of regional dynamic traffic assignment procedures, the state of the practice for highway assignment currently is static equilibrium assignment, even in areas with activity-based travel demand models. Equilibrium assignment is a multipath procedure where vehicle trips are loaded from origin to destination through an iterative process. During each iteration, the trips for each origin-destination TAZ pair are assigned to a single shortest path along the network (each iteration is known as an "all or nothing" assignment). The loadings from the iterations are weighted in a manner that results, at convergence, in the travel times along all paths being equal. This ensures that no driver could improve his travel time by changing his or her path. This property is Wardrop's first principle of equilibrium [58].

Iterative multipath assignment procedures have been in use for decades, with various procedures used to weight the iterations. Among these methods, equilibrium assignment is defined as the procedure that satisfies Wardrop's first principle. Since equilibrium assignment procedures are readily available in modeling software, it is **recommended practice** for all areas for highway assignment. In smaller areas, other multipath methods are considered **acceptable practice**.

In practice, it requires a large number of iterations to achieve true convergence, as noted in a report, "Investigation of New Equilibrium Assignment Methods for the VDOT Travel Demand Models," prepared for VDOT by Old Dominion University (ODU) [59], as well as research done by others. The ODU report recommends that assignments run until a relative gap (a measure of the difference in results between consecutive iterations) of 1E-04 is achieved.

Achieving convergence is important in having a good model since insufficient convergence can result in unexplainable differences between the results of scenarios. The number of iterations required to achieve a relative gap of 1E-04 can be high in networks for large urban areas. Model operational considerations (e.g., run times) can come into play in ultimately setting threshold values. The ODU report notes that the biconjugate Frank-Wolfe algorithm in VDOT's currently adopted modeling software is more efficient than the Frank-Wolfe algorithm in achieving convergence, and it is the **recommended practice** as of 2012.

10.1.2 Time Periods Modeled

In large areas, it is considered **acceptable practice** to perform highway assignment separately for at least three time periods: the morning peak, evening peak, and off-peak periods. These periods comprise a 24-hour average weekday. Most large areas separate the off-peak period into midday and night periods, however, and this is **recommended practice** for these areas in Virginia.

The daily trips are divided into trips by time period prior to assignment. This may be done immediately prior to assignment (i.e., after mode choice) or earlier in the modeling process (after trip generation or trip distribution). In four-step models in Virginia, this is accomplished through the use of factors applied to daily trips by trip purpose and direction (production to attraction or attraction to production). The factors are typically derived from household survey data.

It is sometimes desirable to have traffic volume results for each peak hour (as distinguished from the peak periods which may be two or more hours long). This can be accomplished by further subdividing the time periods for assignment although this is not required practice. Peak hour volumes may be obtained by factoring peak-period volumes, with factors often derived from traffic count data.

Note that the use of fixed factors for peak period and peak hours means that peak spreading is not explicitly considered in four-step models. There are a handful of examples of time-of-day choice models associated with four-step models, which allow peak spreading to be considered. However, these are often complex and difficult to estimate and validate, and so they are not required practice in Virginia.

Smaller areas also may consider assignment by time period if there is a desire for volumes by period. It is considered **acceptable practice** in smaller areas to perform highway assignment for the entire 24-hour average weekday without respect to time periods. However, it is considered **recommended practice** in smaller areas to perform highway assignment for at least three time periods.

10.1.3 Speed-Volume Relationship

To consider the effects of traffic congestion on travel times and speeds, highway assignment processes use relationships of volume, capacity, and speed/time at the link level. These speed-volume relationships, often called "volume-delay functions," may vary by roadway type (and sometimes by time of day).

Another report, "Evaluation of Volume-Delay Functions and their Implementation in VDOT Travel Demand Models," prepared for VDOT by ODU [60] examined three volume-delay functions used in highway assignment: the BPR, Conical, and Akcelik functions.

The BPR function has the following form:

$$T=T_0*[1+\alpha*(V/C)^{\beta}] \qquad (10\text{-}1)$$

Where:

T=average link travel time

T_0=link travel time at free-flow status

V=volume (or demand)

C=capacity

α and β=parameters

The conical function has the following form:

$$T=T_0 * (2+(\alpha^{2}*(1-V/C)^{2}+\beta^{2})^{1/2}-\alpha*(1-V/C)-\beta) \qquad (10\text{-}2)$$

Where:

T =average link travel time

T_0=link travel time at free-flow status

V= volume (or demand)

C =capacity

$\beta=(2\alpha-1)/(2\alpha-2)$, $\alpha>1$

The Akcelik function has the following form:

$$T = T_0+0.25*t*((V/C)-1+((V/C-1)^{2}+(V/C)*8*J/Q/t)^{1/2}) \qquad (10\text{-}3)$$

Where:

T=average link travel time per unit distance (hr)

T_0= free-flow travel time per unit distance (hr)

V= volume or demand (vph)

C = link capacity (vph)

Q = lane capacity (vph)

J= delay parameter

t = flow period (typically 1 hr)

Any of these functions, which are described in detail in this ODU report, are considered both **acceptable practice** and **recommended practice** for all areas. The parameters of the function that is used should be adjusted during model validation to optimize the model results. This report suggests the following acceptable ranges for the two parameters in the BPR formula:

- The value of α should be between 0 and 2; and
- The value of β should be between 1 and 10.

The latest speed data, especially those for interstates, freeways, and expressways, can be used to support the calibration of these parameters (see 10.5 for details).

10.2 Transit Assignment Practice

The policies and procedures for transit assignment practice in Virginia are summarized in Table 10.2. These apply only in regions where transit is modeled explicitly.

Table 10.2 Transit Assignment Practice for Virginia Travel Demand Models

Component	Acceptable		Recommended	
	Small	Large	Small	Large
Assignment method	Shortest path	Shortest path	Multipath	Multipath
Time periods modeled	Daily	Peak and off-peak	Daily	Peak and off-peak

The main inputs to transit assignment include the transit network, described in Section 4.1.3, and the transit person trip tables, which are outputs of the mode choice model. As discussed in Chapter 9, typically there are separate trip tables for transit with walk access and transit with auto access; additional transit submodes also may be modeled. The transit path building process includes various parameters (described in Section 10.4).

Transit assignment determines the routing of transit passengers from origin to destination along shortest paths along the transit network, including access and egress through walking or automobile. Transit assignment procedures in Virginia generally do not consider the effects of capacity constraints on route choice since in most cases capacity of transit vehicles is not a major issue. Multipath assignment procedures are used to reflect the differences among transit riders' values of the time and cost associated with the various components of the transit trip, including time spent riding in transit vehicles, walk and auto access/egress, wait time, and transferring.

10.2.1 Assignment Method

It is considered **acceptable practice** in all areas to perform transit assignment using a single minimized generalized cost path for each origin-destination TAZ pair. This should be adequate in cases where there are few transit options. It is considered **recommended practice** in all areas to use a multipath transit assignment process. Both Cube and TransCAD, which are currently used by VDOT, include such an assignment procedure.

10.2.2 Time Periods Modeled

In some areas, the transit level of service may differ considerably between peak and off-peak periods. For example:

- Some express services may run only during peak periods;
- Service frequency on some routes may be substantially higher in peak periods; and
- Transit fares may vary by time of day, as is the case with the WMATA rail service.

In such cases, it is desirable to assign transit trips separately for peak and off-peak periods. The peak periods need not be defined in exactly the same way as for highway assignment.

It should be noted that in most cases, auto access or egress is at the home end of the trip, regardless of whether that represents the origin of the trips – the home end is the destination for trips made by persons returning home. The simplest way to deal with this issue is to assign transit trips with auto access from the production (home) end to the attraction (nonhome) end, regardless of whether the traveler is leaving from or returning home. This reduces the number of transit paths required for assignment and provides the opportunity to combine the morning peak and evening peak periods into a single peak period for transit assignment, further reducing computation. In a combined peak period, the same paths are used for trips leaving from and returning home. Since this process presents trips returning home as if they had boarded the transit vehicle at the transfer point between the transit and auto egress trip segments, the boardings and alightings at stations must be determined by treating half of the boardings as alightings. This simplification is not exact (since travelers may make one direction of a round trip during the combined peak period and the other direction in the off-peak period), but this approximation is usually good enough for most planning purposes.

It is considered both **acceptable practice** and **recommended practice** for small areas to perform transit assignment at the daily level. It is considered both **acceptable practice** and **recommended practice** for larger areas to perform transit assignment for two periods, peak (combined) and off-peak.

10.3 Highway Network Skimming

Highway network skimming is performed using modeling software sometime prior to trip distribution, the first model component for which it is a required input. There are two variables for which highway skim matrices are produced, travel time and distance. Sometimes toll cost may be skimmed as well, if priced roadways exist in the network. Other highway-related costs are either related to distance (auto operating cost) or are related to the attraction end of the trip (parking cost) and need not be skimmed. For models involving HOV facilities, the highway network is prepared with special limit codes on HOV facilities and a separate skim table is produced including time and distance employing HOV links where applicable (the HOV links are not considered in the non-HOV skim table in such cases).

In some models, especially larger models and those for which feedback loops are used (see Chapter 11), the skims represent "congested" travel times from a loaded network. Because models will converge more quickly if the starting travel times are closer to the final times, it is efficient to create some type of loaded network to skim. Sometimes this is done by assigning a vehicle trip table developed from another source, such as the expanded household survey data.

The process of creating highway network skims in modeling software is straightforward, with the user needing to supply only the highway network to be used and to define the variables to be skimmed. The paths for which the skims are produced reflect the least generalized cost paths. If a loaded network is skimmed, and the assignment used for loading the network was a multipath assignment, there may be multiple paths used for assignment; however, the skims will reflect the shortest path found by the modeling software path building process. If the assignment was a reasonably well converged equilibrium assignment, this is not really an issue since the travel times along all used paths for each origin-destination pair are approximately the same. The distances may vary among the paths used, but usually they are not very different from the distance along the shortest travel-time path found by the modeling software.

10.4 Transit Network Skimming

Transit network skimming is somewhat more complex than highway network skimming, for two reasons:

1. Skim matrices for more variables need to be produced. These variables typically include transit in-vehicle time, wait time, transfer time, walk access and egress time, auto access time, and fare. Sometimes the number of transfers is skimmed.
2. The best paths are determined not by a single variable such as travel time but by a weighted combination of the various components of transit level of service (time and cost), often the same variables for which skim matrices are produced.

The weights used in combining the effects of the different variables should be consistent with the relative values of the coefficients of the variables in the mode choice model's utility function (i.e., the parameters B_{ik} in Equation 9-2). Since the mode choice parameters may vary by trip purpose, it is customary to use the relative weights from the home-based work mode choice model.

Multipath transit path building algorithms in modeling software allow the creation of transit skims from multiple "best" paths. If such a procedure is used, this means that the particular values for an origin-destination TAZ pair in the skim matrices may not correspond to any particular path.

Note that the FTA guidance presented in Section 9.1.5 is relevant to the path building procedures.

10.5 Highway Assignment Validation

10.5.1 Data Sources for Highway Validation

The main sources of data for validation of highway assignment include the following:

- **Traffic counts** have the best information on link-level volumes and also can be used to produce measures of vehicle-miles traveled (VMT). Traffic count data used for highway assignment validation should be directional if peak and off-peak periods are being modeled and should be segmented by these time periods. Vehicle classification counts are needed to validate truck volumes from the assignment process. The primary source for traffic count data in Virginia is the Traffic Engineering Division, Traffic Monitoring Section (see also Section 4.2.3). It must be noted that traffic counts can have substantial variation; a good discussion of this issue can be found in Section 9.1.1 of the FHWA Validation Manual [38]. For validation, only traffic counts with the highest quality coding should be used, and it is necessary to exclude those with quality coded below "G." Continuous count data (with quality coding of A and B) have the highest quality and should receive the highest weights during validation; short term traffic count data are most common but may be substantially different from the "true" average daily traffic for a link, even when the traffic count data are adjusted for day of week and seasonal variation. Link counts for subclassifications such as time-of-day or vehicle classification are also subject to substantial variation.
- **Speed data –** Speed data that can be used in highway assignment model validation includes data from standardized approaches and field studies (see also Section 4.2.4). The data collected can vary from simple point-to-point travel times to run times, cruise times and signal delay times, delay times due to incidents, and in some studies, coincident traffic counts on the facilities traversed. As with traffic count data, travel time and speed studies may be subject to substantial variation depending on the day or days the data are collected. Standardized approaches include using commercial sources (e.g., INRIX or Tom Tom), archived real time data from VDOT road sensors, and the FHWA National Performance Management Research Data Set).
- **HPMS –** The Highway Performance Monitoring System (HPMS) estimates VMT from traffic counts. Regional VMT estimates provide a basis for comparison with modeled VMT. However, prior to using the observed regional VMT based on the

HPMS data, the consistency of the HPMS data and the modeled data should be verified. Consistency checks should include the HPMS area covered versus area covered by the travel model, the facilities included in HPMS (e.g., local streets) versus facilities included in model; and whether VMT estimates are based on average annual daily traffic or average annual weekday traffic.

- **Other data sources –** Various data sources that include some bases for comparison of aggregate model outputs include the NHTS, *NCHRP Report 716* [3], and the FHWA Validation Manual [38].

10.5.2 Highway Assignment Validation Checks

Table 10.3 summarizes the model validation checks for highway assignment.

Table 10.3 Highway Assignment Validation Procedures for Virginia Travel Demand Models

Type of Check	Model Region Size	
	Small	**Large**
VMT by link group (facility type, geographic subregion, etc.)	See Table 10.4	See Table 10.4
R^2 between modeled volumes and counts on links	0.92	0.90
Percent root mean square error	See Table 10.5	See Table 10.5
Cordon line and screenline volume checks	< 54,000: ± 10 percent ≥ 54,000 and < 250,000: see Figure 10.2 ≥ 250,000: ± 5 percent	< 54,000: ± 10 percent ≥ 54,000 and < 250,000: see Figure 10.2 ≥ 250,000: ± 5 percent
Cutline volume checks	< 250,000: see Figure 10.2 ≥ 250,000: ± 5 percent	< 250,000: see Figure 10.2 ≥ 250,000: ± 5 percent
Speed checks	Conduct aggregate checks for congested and uncongested links separately and disaggregate checks of individual links Conduct reasonableness checks (speed versus V/C plots and speed scatterplots)	Conduct aggregate checks for congested and uncongested links separately and disaggregate checks of individual links Conduct reasonableness checks (speed versus V/C plots and speed scatterplots)

Generally, highway assignment checks consist of comparisons of base-year model outputs, based primarily on link volumes, to observed data from traffic counts. Many comparisons, such as VMT and screenline, cutline, and cordon line volumes, are based on aggregations of data from the link volumes. If observed speed data are available, output model speeds may be compared to the observed speed data for the base year, especially freeways and expressways.

If highway assignment is performed for peak and off-peak time periods, the validation checks described in this section should be performed for the assignment results for each period, as well as for the entire average weekday (the sum of all periods). The best way to perform these checks is to first perform the validation checks for the entire day, and when the daily assignment results have been sufficiently validated, to then check the results for each time period. So the same set of checks (e.g., VMT, R^2, percent root mean square error, screenline, etc.) would be performed multiple times, first for the entire daily results, and then for each period of interest (a.m. peak, p.m. peak, etc.). Because the daily checks will verify that the overall amount of highway travel is reasonable, the time period checks are important mainly to verify whether the split of travel among time periods is reasonable. It is important to note that because volumes for periods of a few hours are substantially lower than daily volumes, the guidelines involving percentages of differences are necessarily somewhat looser than those for daily results. For example, the guidelines for checks of percent root mean square error provide higher thresholds for differences for lower volume groups. Since the distribution of peak period link volumes will be skewed toward the lower volume groups compared to daily volumes, more links will be examined using these higher thresholds.

Checks of truck volumes should be conducted separately in addition to checks of total volumes. The vehicle classification traffic count data are used in these comparisons.

It is critical to note that the guidelines presented in Table 10.3 should **not** be treated as pass-fail tests for model validation. Matching or exceeding the guidelines is not sufficient to determine the validity of a model, nor is it a requirement for a validated model. Experience has shown that models can be overcalibrated; making too many changes to attempt to meet validation guidelines can decrease a model's predictive capability. If the model meets most validation checks and is close on the remaining ones, it would be better not to make unjustified adjustments to model parameters or data simply to achieve a better fit. For example, inserting K-factors without a reasonable explanation to achieve a better match with observed origin-destination patterns could reduce the explanatory power of a trip distribution model for forecasting.

VMT Checks

Base-year VMT produced by the model can be compared to observed VMT estimated from the traffic count data (for links with counts) or from HPMS data. The VMT checks should be made for the region and by market segment. Markets may include facility type, area type, and geographic subdivision (e.g., county or superdistrict).

As distinguished from the tests described later in this section, VMT checks provide an overall modeling process check. Different information regarding the modeling process can be inferred from each level of the summaries:

- *Regional VMT summaries* provide an indication of the reasonableness of the overall level of travel. The results help confirm that the trip generation, trip distribution, and mode choice models, as well as the assignment process, are performing reasonably.

- *VMT summaries by facility type* provide an overall indication of the operation of the assignment procedures. The results of these summaries might indicate issues with free-flow speeds, link capacities, or volume-delay functions, any of which may vary by facility type.
- *VMT summaries by geographic area* may be useful for uncovering geographic biases in the modeling process. These biases might relate to previous steps in the modeling process.
- *VMT summaries by combinations of the above strata* may provide additional diagnostic information if one of the above summaries indicates a validation problem.

Table 10.4 lists some example guidelines used for the match between modeled and observed VMT by facility type and area type for some other states, including Ohio, Florida, and Michigan, as well as guidelines prepared by FHWA in 1990.

Table 10.4 Example VMT Guidelines by Functional Class and Area Type

	Modeled Versus Observed VMT				
		Florida[b]			
Stratification	**Ohio[a]**	**Acceptable**	**Preferable**	**Michigan[c]**	**FHWA[c]**
Functional Class					
Freeways/Expressways	±7%	±7%	±6%	±6%	±7%
Principal Arterials	±10%	±15%	±10%	±7%	±10%
Minor Arterials	±10%	±15%	±10%	±10%	±15%
Collectors	±15%	±25%	±20%	±20%	±20%
All Links		±5%	±2%		
Area Type					
CBD	±10%	±25%	±15%		
Fringe	±10%	±25%	±15%		
Urban	±10%	±25%	±15%		
Suburban	±10%	±25%	±15%		
Rural	±10%	±25%	±15%		

Note: [a] G. Giaimo, "Travel Demand Forecasting Manual 1 – Traffic Assignment Procedures," Ohio Department of Transportation, Division of Planning, Office of Technical Services, August 2001.

[b] Cambridge Systematics, Inc., "Model Calibration and Validation Standards, FSUTMS-Cube Framework Phase II," 3-16, Table 3.9, 2008 [61].

[c] Cambridge Systematics, Inc., "Travel Model Validation and Reasonableness Checking Manual," 2010 [38].

Link Volume Checks

Traffic volume-related checks compare modeled to observed traffic volumes at the link level. Consequently, the amount of difference between the modeled and observed traffic for each link contributes directly to the overall measure of closeness even when the results are aggregated in different ways. This is in contrast to the VMT checks described above where a positive difference on one link can cancel a negative difference on another link. The traffic volume-related checks described in this section focus on traditional measures that are scalable and easily explained: percent root mean square error (%RMSE) and coefficient of determination (R^2).

Percent Root Mean Square Error (%RMSE)

%RMSE for a set of links can be calculated using Equations 10-1 and 10-2.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}\left[(\mathrm{Count}_i - \mathrm{Model}_i)^2\right]}{N}} \qquad (10\text{-}1)$$

$$\%\mathrm{RMSE} = \frac{\mathrm{RMSE}}{\left(\frac{\sum_{i=1}^{N}\mathrm{Count}_i}{N}\right)} \times 100 \qquad (10\text{-}2)$$

Where:

Count$_i$ = The observed traffic count for link *i*;

Model$_i$ = The modeled traffic volume for link *i*; and

N = The number of links in the group of links, including link *i*.

%RMSE is a measure of accuracy of the traffic assignment measuring the average error between the observed and modeled traffic volumes on links with traffic counts. As such, %RMSE should be summarized by facility type or by link volume group. Summarizing the measures by geography also can provide good validation information, especially if the measures continue to be stratified by facility type or volume group.

Table 10.5 provides guidelines for target %RMSE by volume group, based on guidelines used in Florida [61]. Figure 10.1 depicts graphically the %RMSE guidelines in three states (Florida, Ohio, and Oregon). Guidelines for other segmentation plans, such as facility types and time periods, can be derived from Table 10.5 by noting the average volume for each segment. Table 10.6 shows the guidelines for target %RMSE by facility types.

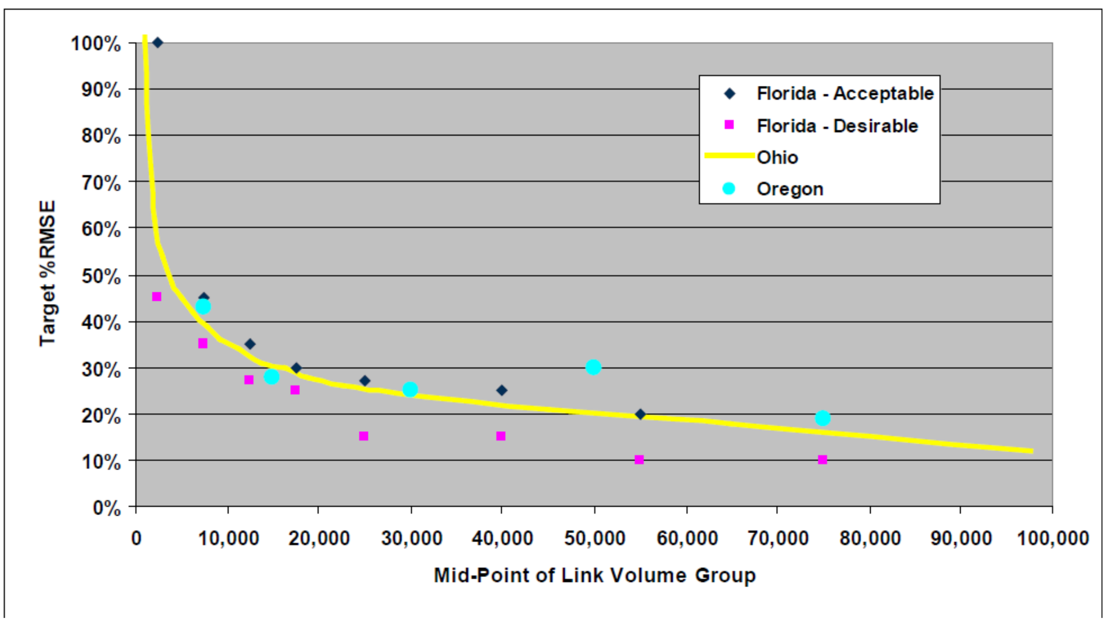
Table 10.5 Percent RMSE Guidelines

Volume Range	%RMSE Guideline
Less than 5,000	100%
5,000-9,999	45%
10,000-14,999	35%
15,000-19,999	30%
20,000-29,999	27%
30,000-49,999	25%
50,000-59,999	20%
Greater than 60,000	19%
Areawide (daily)	40%

Source: Adapted from Cambridge Systematics, Inc., "Model Calibration and Validation Standards, FSUTMS-Cube Framework Phase II," 2-21, Table 2.11, 2008 [61].

Note: The areawide daily guideline is based on VDOT practice (the FDOT areawide guideline is 45%).

Figure 10.1 Example %RMSE Guidelines



Sources: Cambridge Systematics, Inc., "Travel Model Validation and Reasonableness Checking Manual," 9-20, Figure 9.8, 2008 [38]; Ohio – G. Giaimo, "Travel Demand Forecasting Manual 1–Traffic Assignment Procedures;" Florida and Oregon - Cambridge Systematics, Inc., "Model Calibration and Validation Standards, FSUTMS-Cube Framework Phase II," 2008 [61].

Table 10.6 Percent RMSE by Facility Type Guidelines

Volume Range	%RMSE Guideline
Freeways/Expressways	20%
Principal Arterials	35%
Minor Arterials	45%
Collectors	100%

R-Squared (R^2)

Pearson's product-moment correlation coefficient (*R*) is a standard statistical measure available in spreadsheet programs and other readily available software packages. *R* is a dimensionless index that ranges from –1.0 to 1.0 inclusive that reflects the extent of a linear relationship between two data sets. It is calculated as shown in Equation 10-3.

$$R = \frac{N \times \left[\sum_{i=1}^{N}(\text{Count}_i \times \text{Model}_i)\right] - \left(\sum_{i=1}^{N}\text{Count}_i\right) \times \left(\sum_{i=1}^{N}\text{Model}_i\right)}{\sqrt{\left[\left(N \times \sum_{i=1}^{N}\text{Count}_i^2\right) - \left(\sum_{i=1}^{N}\text{Count}_i\right)^2\right] \times \left[\left(N \times \sum_{i=1}^{N}\text{Model}_i^2\right) - \left(\sum_{i=1}^{N}\text{Model}_i\right)^2\right]}} \tag{10-3}$$

Where $Count_i$, $Model_i$, and *N* are as defined as in Equations 10-1 and 10-2.

The coefficient of determination, R^2, which is simply the square of *R*, is typically interpreted as the proportion of the variance in a dependent variable that is attributable to the variance in an independent variable. This traditional interpretation does not hold for traffic assignment validation since the modeled traffic assignment is not dependent on the traffic count, or vice versa.

In effect, R^2 has been assumed to be a measure of the amount of variation in traffic counts "explained" by the model. R^2 must be used with caution. An R^2 value for all links in the region implies that links with high capacities (e.g., freeways) can, and usually do, carry more traffic than links with low capacities (e.g., local streets). As such, the value of R^2 probably says more about the coding of facility type and number of lanes than about how the model and assignment are performing.

Scatterplots of modeled traffic volumes versus the observed traffic volumes can provide useful visual validation tools. These can be used in connection with the R^2 summaries.

Cordon Line, Screenline, and Cutline Checks

Comparison of modeled volumes to observed counts for sets of critical links, especially along cordon lines, screenlines, and cutlines, are useful for assessing model quality. Cordon lines, screenlines, and cutlines are defined in Section 4.2.3. It is **recommended practice** that small model regions include at least 10 percent of their non-centroid links in their screenline, cordon line, and cutline coverage. For large model regions, it is recommended that at least 5 percent of their non-centroid links be included in their screenline, cordon line, and cutline coverage. Below are summarized the definitions and the relevant VDOT guidance for validation measures for each:

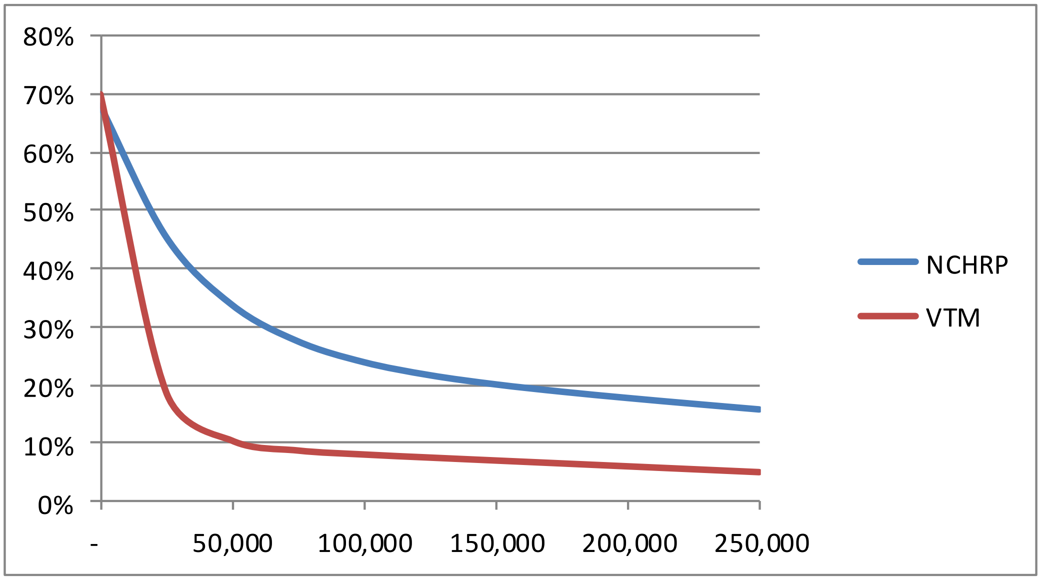
- A cordon line is a line that encloses a subregion of the model, often a CBD, city, or major activity center. For both small and large model regions, the estimated volume for highway cordon lines should be within 10 percent of observed count volumes for cordon volumes with less than 54,000 observed count volume. Higher volume cordon lines should follow the same guidelines used for highway cutlines, discussed below. For cordon lines with observed count volumes greater than 250,000, cordon line volume should be within 5 percent of observed count volumes.
- A screenline is a line that crosses the entire model region, effectively splitting the model region into two parts. For both small and large model regions, the estimated volume for highway screenlines should be within 10 percent of observed count volumes for screenline volumes with less than 54,000 observed count volume. Higher volume screenlines should follow the same guidelines used for highway cutlines, discussed below. For screenlines with observed count volumes greater than 250,000, screenline volume should be within 5 percent of observed count volumes.
- A cutline is a line that crosses part of the model region, meaning that it is possible to build paths from one side of the cutline to the other that go around the cutline. The allowable deviation in cutlines should vary according to the total volume of the cutline. Lower volume cutlines should have higher allowable deviations while higher volume cutlines have lower allowable deviations. This is discussed further below.

NCHRP Report 255 contains a maximum desirable deviation curve that traditionally has been used by model analysts to assess allowable deviations for cutlines depending on the volumes involved [62]. VDOT staff have developed a custom equation and curve for allowable cutline deviation for the Virginia Transportation Modeling (VTM) system which is shown as Equation 10-4. Both curves are illustrated in Figure 10.2. The VTM curve maintains flexibility for low volume cutlines while providing meaningful guidelines for cutline analysis. For cutlines with observed count volumes of 250,000 or greater, cutline volume should be within 5 percent of observed count volumes.

$$\text{Maximum Allowable Deviation} = \frac{60 * e^{(-0.075 * C/1000)} + \left((-0.02) * (C/1000)\right) + 10}{100} \qquad (10\text{-}4)$$

Where C = Cutline Count Total

Figure 10.2 VDOT Maximum Desirable Deviation in Total Cutline Volumes



Source: Adapted from N. Pedersen and D. Samhdahl, "NCHRP Report 255," 41, Figure A-3, 1982 [62].

Speed Checks

Speed checks compare modeled speeds to observed data from travel-time studies or, possibly, spot speed data for facilities not affected by intersection controls. The speed checks are focused on time of day or peak-period assignment results. While they can be easily calculated from VMT and vehicle-hours of travel (VHT) summaries for links, 24-hour average speeds are not very meaningful.

It is somewhat more difficult to define validation tests focused on speeds than it is to define traffic volume-related validation checks. While modeled speeds can easily be calculated for each link, the modeled speeds are directly impacted by the quality of the assignment results. Thus, errors in assigned speeds might result from errors in the estimation of speeds or from errors in assigned traffic volumes. This issue might be addressed by filtering the links included in the test to include only those links where the assigned traffic volume is relatively close to the observed traffic count.

Examples of speed reasonableness checking include:

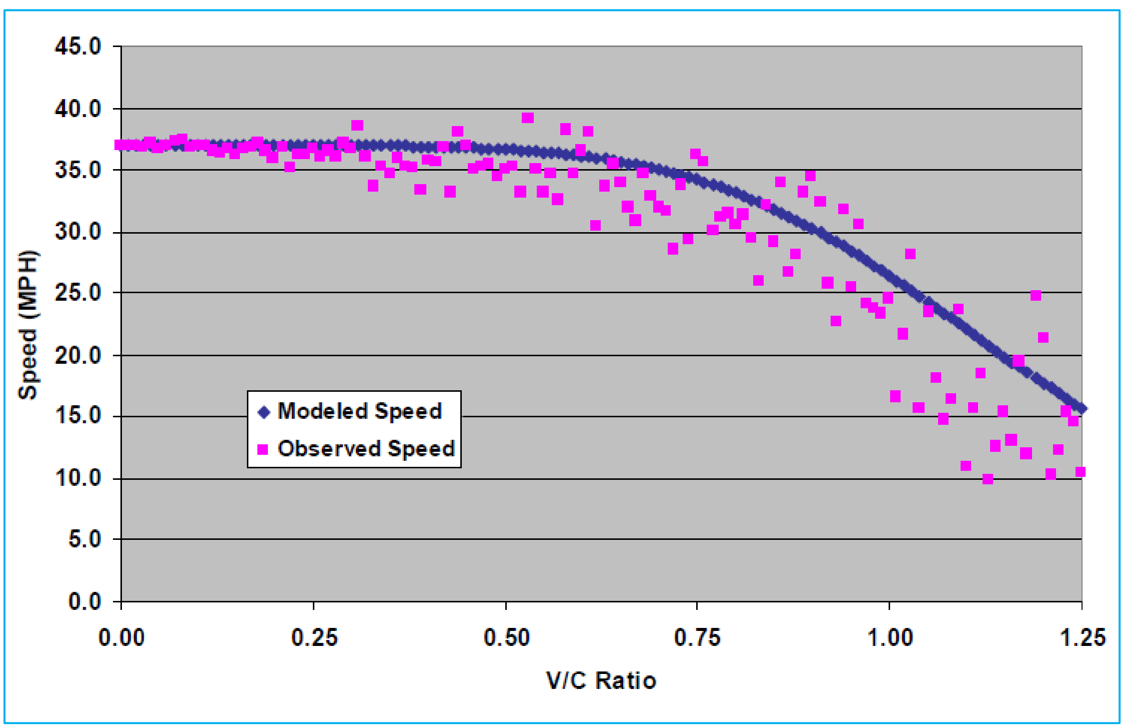
- Scatterplots of modeled versus observed speeds for peak and off-peak periods, similar to the scatterplots of modeled versus observed volumes; and
- Speed versus V/C plots for peak and off-peak periods, by facility types.

An initial validation check of modeled speeds can be prepared by producing scatterplots of modeled versus observed speeds. The scatterplots might look like the ones used for modeled volumes versus traffic counts. The scatterplots should be produced by facility type and, if possible, by link volume group within the facility type grouping. The stratification by volume group would address two primary issues:

- It is probably more desirable to match traffic speeds on high volume links than on low volume links; and
- Speeds on low volume links should be close to free-flow speeds; if the free-flow speeds do not match reasonably, the veracity of the volume delay functions or the free-flow speed inputs can be questioned, especially if the speeds for high volume links match closely.

Both observed and modeled speeds can be plotted against volume/capacity ratios for peak and off-peak periods. The observed speeds should be plotted against the volume/capacity ratio for the observed traffic count at the time the speed information was collected. The modeled speeds should be plotted against the modeled volume/capacity ratio. The plots should be produced by facility type. Figure 10.3, as an example of such a plot, can be used for verifying volume delay functions for the assignment. It is just as valid to plot the modeled speeds using the specified volume-delay function for a specified facility type. The comparison plots remove the impacts of differences in modeled traffic volumes and observed traffic counts inherent in the scatterplots of modeled versus observed speeds. The plot shown in Figure 10.3 suggests that the modeled speeds do not decrease quite quickly enough as the volume/capacity ratio increases.

Figure 10.3 Example Comparison Plot of Speeds versus Volume/Capacity Ratios



Source: Cambridge Systematics, Inc., "Travel Model Validation and Reasonableness Checking Manual," 9-16, Figure 9.7, 2010 [38].

For interstates and freeways, it is **recommended practice** to conduct aggregate and disaggregate checks. Links with speed data can be classsified as congested links and uncongested links. For example, the period-specific speeds (AM, PM, and MD) are compared to night-time or free flow speeds, and the links are congested if the difference is 10 mph or more. For the aggregate checks, the following steps can be taken:

- Confirm that aggregate volume checks (e.g., VMT) show good results
- For all interstate/freeway links with speed data, compare average modeled speed for each time period to average observed speed
    - If more than 5 mph in difference for a period, consider revising conversion factor (hourly to peak period)
- For uncongested links with speed data, compare average modeled speed for each time period to average observed speed
    - If more than 5 mph in difference for a period, consider revising conversion factor (hourly to peak period)
- For congested links with speed data, compare average modeled speed for each time period to average observed speed
    - If more than 5 mph in difference for a period, check percentage of daily volume in the period, consider revising conversion factor (hourly to peak period), and/or consider revising capacity values

For disaggregate checks, modeled speeds on individual links with speed data should be examined for deviation from the observed speeds.

- If more than 5 mph in difference in the same direction for all periods, consider revising free flow speed values
- If more than 5 mph in difference in the same direction for peak periods:
    - Compare modeled volume to observed counts—if off in the same direction (e.g., volume high, speed low), perform normal link level assignment calibration
    - Consider revising capacity values

The time-of-day and hourly factors vary considerably by regions. The estimation of these factors is generally based on the temporal distribution of trips or traffic, which can be obtained from household travel surveys, traffic counts, or Big Data sources such as StreetLight. Table 10.7 shows the peak period and peak hour shares of trips for each trip purpose, by direction for home-based trips derived from 2009 NHTS data for weekdays [3].

Table 10.7 Peak Period and Hourly Shares of Trips by Trip Purpose and Direction

	Home-Based Work		Home-Based Nonwork		Nonhome-Based	All Trips
	From Home	To Home	From Home	To Home		
All Modes						
7-9 AM Peak Period	22.0%	0.2%	11.8%	2.3%	10.0%	14.0%
3-6 PM Peak Period	2.6%	25.7%	9.5%	15.3%	24.7%	25.3%
7-8 AM Peak Hour	14.3%	0.1%	7.0%	1.0%	4.9%	7.9%
5-6 PM Peak Hour	0.5%	10.5%	3.7%	4.9%	7.3%	8.5%
Auto Modes						
7-9 AM Peak Period	21.8%	0.2%	11.1%	2.2%	9.9%	13.6%
3-6 PM Peak Period	2.6%	25.7%	9.5%	15.3%	25.0%	25.4%
7-8 AM Peak Hour	14.3%	0.1%	6.5%	1.0%	4.9%	7.7%
5-6 PM Peak Hour	0.5%	10.6%	3.7%	5.1%	7.4%	8.7%
Transit Modes						
7-9 AM Peak Period	27.0%	0.2%	14.2%	0.5%	13.5%	17.4%
3-6 PM Peak Period	1.8%	25.1%	5.7%	14.8%	24.7%	23.3%
7-8 AM Peak Hour	17.1%	0.0%	7.6%	0.1%	6.1%	9.5%
4-5 PM Peak Hour	0.4%	10.8%	1.9%	5.0%	8.0%	8.3%

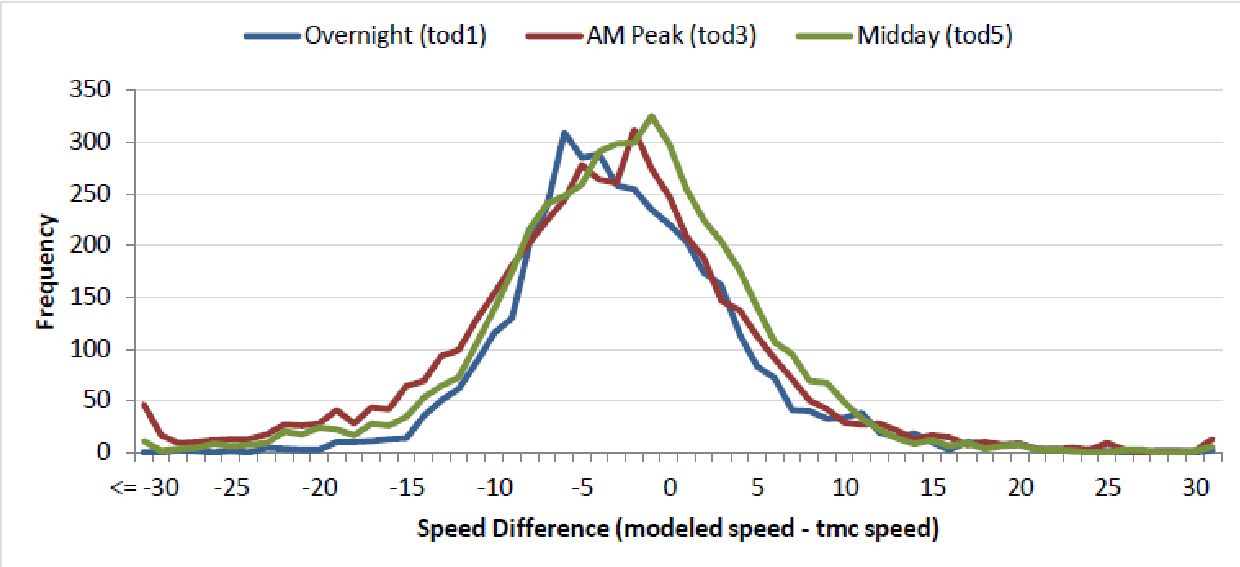
Source: Adapted from Cambridge Systematics, Inc., et al., "Travel Demand Forecasting: Parameters and Techniques, NCHRP Report 716," c-22 to c-24, Tables C.11, 2012 [3]

Other measures that are useful for checking speed reasonableness from the model include:

- Travel time difference frequency distribution diagrams;
- Origin-destination travel time;
- Travel times on selected routes; and
- Travel time contours.

The difference between modeled travel speeds and observed travel speeds can be examined by plotting the frequency distribution curves of speed difference, as shown in Figure 10.4. These distribution curves allow for examining if the speed differences are systematic (systematically over- or under-estimated speeds), or due to other specific reasons that need to be further investigated. These curves should be plotted by facility type and by time period.

Figure 10.4 Frequency Distribution Curves of Speed Difference



Source: Chicago Metropolitan Agency of Planning, "Trip-Based Travel Demand Model Validation Report," 40, Figure 16, 2017.

The observed and modeled travel times of selected origin-destination zone pairs can be derived from the travel model and plotted on a diagram for visual examination. These O-D travel times are generated using the model's network skimming process with observed or modeled link speed (or travel time) data of individual model links. The observed skim travel time can be developed if most of the road segments on the network have observed travel speed (or travel time) data. For road segments without observed speed data, the modeled estimated link speeds could be used instead.

Comparison of travel times on selected travel route is also a traditional mean to validate the highway skimming and assignment process. The differences between modeled speeds and surveyed speeds of specific travel routes can also be examined if travel speeds data are available for each route segment along the travel routes. Floating car are often used to collect travel times on the selected routes. For model validation, the selected routes should cover a wide range of route types and cover the model area as evenly as possible. The length of routes should be in the range of 5 to 10 miles.

A travel time contour diagram is an effective mean to visually examine the difference between the observed and modeled travel time to or from a specific location. The observed travel times could also be derived from the skimming process with observed travel speed/time data attached to road segments of the model network. The observed travel times can be obtained from the Google point-to-point travel time dataset.

A proper balance should be established between validating to traffic counts and observed speeds, as frequently there is a direct conflict between model adjustments used to match volumes versus speeds.

Sensitivity Testing

The FHWA Validation Manual presents some sensitivity tests for highway assignment [38]. These are shown below:

- *Regional sensitivity* – Check reasonableness of the change in VMT in response to changes in total trips. Change trips by a factor (e.g., 1.5) and check to see whether total VMT changes by a similar factor. If there is little congestion in the region, VMT should increase by a similar factor. If there is substantial congestion, VMT should increase by more than the factor.
- *Localized sensitivity* – Modify key network elements and review assignment results for changes and reaction to network elements (using a fixed trip table). For example, remove a key bridge or limited access facility and review the impact on traffic using volume difference plots between the original and modified alternatives.
- *Oversensitivity* – For congested networks, make a minor change to a network (e.g., add a lane of traffic to a minor arterial link) and reassign a fixed trip table using same number of iterations and closure criteria. Review the impact on traffic using volume difference plots between the original and modified alternatives. Traffic impacts should be very localized.

It makes sense to perform each of these tests several times, using different values or changes to the networks in different locations. Changes should be made in both directions, i.e., both adding and removing highway facilities.

The assignment results can be used to check the sensitivity of the entire model system to changes in socioeconomic data inputs. The value of a key input, such as the number of households, population, retail employment, or nonretail employment, can be increased or decreased for a specific TAZ, and the effect on total travel, as measured by VMT, can be examined. This type of check is usually repeated with various levels of change, in both directions, and is performed for TAZs of various area types within the region.

10.5.3 Highway Assignment Model Calibration and Troubleshooting

Since assignment is the last step in the modeling process, issues discovered during the model checks described in Section 10.5.2 may imply errors in almost any component of the model process, as well as assignment model parameters, input data (networks/skims or trip tables), or highway or transit path building procedures. Some of the typical problems that may be evident from these tests include the following:

- Low, high, or unrealistic base-year modeled link volumes compared to traffic counts: Check network coding (speeds, capacities, turn penalties, etc.) on these links, nearby/ adjacent links, and links on competing paths; check TAZ connections and loading at centroids; and check traffic count data for accuracy.
- Uneven facility loading on parallel competing routes: Review centroid connections, review facility and area type coding and input starting speeds for assignments; review

TAZ structure and number of TAZs (may need to have finer spatial resolution); and review final congested speeds and volume-delay functions.

- Modeled travel times/speeds not consistent with observed data: Review facility and area type coding and input starting speeds for assignments; review final congested speeds and volume-delay functions; compare average modeled speed for each time period to average observed speed; consider revising conversion factor (hourly to peak period).
- Links with zero assigned volume: Check network coding (including nearby or competing links) for continuity, stub links, centroid connector locations, and attributes such as free-flow speeds and capacities.
- Links with very high assigned volume/capacity ratios: Check network coding (including nearby or competing links) for centroid connector locations and attributes such as free-flow speeds and capacities.
- Links with estimated speeds deviated significantly from observed speeds: Compare modeled volume to observed counts, consider revising free flow speed values or revising capacity values.

10.6 Transit Assignment Validation

10.6.1 Data Sources for Transit Assignment Validation

The main sources of data for validation of transit assignment include the following:

- **Transit ridership counts** have the best information on the total amount of travel by transit, usually at the route level, and sometimes at the stop level, especially for fixed guideway services. Since these counts represent unlinked trips, they are consistent with the boarding volumes that are the outputs of transit assignment.
- **Park-and-ride lot utilization –** Regions that have an established park-and-ride system may collect parking lot utilization data for the various lots. The data collected may range from the number of spaces used on a daily basis to the number of vehicles parking at the lot on a daily basis to license plate surveys of parking lots. Vehicle counts at park-and-ride lots are superior to counts of used parking spaces since the vehicle counts provide a clearer picture of park-and-ride lot demand.
- **Transit rider survey –** The transit rider survey (see Section 4.2.1) is a source of information for validation of some outputs of transit assignment models, such as path checks and transfer activity.

10.6.2 Transit Assignment Validation Checks

Table 10.8 summarizes the model validation checks for transit assignment.

Table 10.8 Transit Assignment Validation Procedures for Virginia Travel Demand Models

Type of Check	Model Region Size	
	Small	**Large**
Boardings, by route group and type of transit	Reasonableness checks only	Reasonableness checks only
Transfer rate	Reasonableness checks only	Reasonableness checks only

Generally, transit assignment checks consist of comparisons of base-year model outputs, based primarily on route boardings, to observed data from ridership counts. Since most regions have relatively few transit lines, checks by line are typically reported for each line although the comparisons may need to be made for groups of routes to achieve sufficient ridership for comparison.

If the transit assignment is performed for peak and off-peak time periods, the validation checks described in this section should be performed for the assignment results for each period, as well as for the entire average weekday (the sum of all periods). As is the case with highway assignment checks, the best way to perform these checks is to first perform the validation checks for the entire day, and when the daily assignment results have been sufficiently validated, to then check the results for each time period.

Boarding Count Checks

Most transit assignment checks begin with the comparison of modeled to observed transit boardings. In addition to total system boardings, these comparisons may include boardings by line and by mode. Validation checks typically consist of comparing absolute and relative differences between modeled and observed boardings by line.

Comparison of modeled to observed boardings at major transfer points provides another set of validation checks. The major transfer points may include park-and-ride lots, fixed guideway transit stations (e.g., light rail stations), and bus transit centers or "pulse points."

The assignment of an "observed" transit trip table (based on expanded data from a transit rider survey) can be valuable in providing an "in-between" data point for transit assignment validation. If the modeled boardings resulting from the assignment of the "observed" transit trip table match the observed boardings reasonably well, but the modeled boardings resulting from the assignment of the transit trip table from the mode choice model do not match up well with the observed boardings, issues with the mode choice model or preceding models such as trip distribution may be indicated. If the results from assignments using both trip tables ("observed" and from the mode choice model) match each other well but not the observed boardings, there may be issues with the transit network or path building procedures (although checks of the observed data, boardings and transit survey, also should be performed).

Transit Rider Survey-Based Checks

If a transit rider survey is available, the observed regional transfer rate or boardings per linked trip can be estimated. This information also can be estimated from boarding counts if the operator provides transfers and records boardings by fare payment type. Modeled boardings per linked trip can be estimated from the transit assignment results. As with previous checks, this comparison can be made based on the assignment of either observed transit trip tables or modeled trip tables.

Sensitivity Testing

The sensitivity checks for transit assignment are very much related to those for mode choice. Changes in input variables can change modeled transit mode shares and therefore modeled transit ridership. Specific checks focusing on transit assignment might include changing key transit routes or segments and reviewing assignment results using a fixed transit trip table. For example, a route might be removed, or its headway changed, and the effects on nearby routes checked. It makes sense to perform each of these tests several times, using different values or changes to the networks in different locations.

10.6.3 Transit Assignment Model Calibration and Troubleshooting

As discussed in Section 10.5.3, since assignment is the last step in the modeling process, issues discovered during the model validation checks described in Section 10.6.2 may imply errors in almost any component of the model process. However, unlike the case of highway assignment, it might be possible to isolate transit assignment issues to the transit assignment process if an observed transit trip table from an on-board survey is available. Some of the typical problems that may be evident from these tests include the following:

- <u>Low or high boardings/ridership compared to route/stop boardings</u>: Check network coding (stops, etc.) on the affected routes/stops, nearby/adjacent routes, and competing routes; check transit access links; check run times, speeds, and/or dwell times for routes; check level of zonal resolution and transit walk access percentages; check trip tables for consistency between trips in corridor and observed boardings; modify path building/assignment parameters; if using multipath assignment procedures, investigate changes in route "combination" factors; investigate changes to transfer penalties; investigate changes to relationships between wait time, out-of-vehicle time, in-vehicle time, and transit cost.

- <u>Low or high boardings per linked trip</u>: Review walk access/egress assumptions, investigate changes to transfer penalties, modify assignment procedures, increase market segmentation, modify path building/assignment parameters, if using multipath assignment procedures, investigate changes in route "combination" factors, investigate changes to transfer penalties, investigate changes to relationships between wait time, out-of-vehicle time, in-vehicle time, and transit cost.

Note that these actions are intertwined with those for the mode choice model validation (see Section 9.2.3).

CHAPTER 11. FEEDBACK LOOPS

This chapter describes the process of feeding back travel times that are outputs from the highway assignment process to be used as inputs in earlier model steps. This process is needed in regions with substantial highway congestion. Generally, in small model areas, it is considered **acceptable practice** not to use feedback loops, but it is a **recommended practice**. It is considered both **acceptable practice** and **recommended practice** in larger regions to use feedback loops.

The policies and procedures for external travel modeling practice in Virginia are summarized in Table 11.1.

Table 11.1 Practice in Feedback for Virginia Travel Demand Models

	Acceptable		Recommended[a]	
Component	**Small**	**Large**	**Small**	**Large**
Use of feedback loops	No	Yes	Yes	Yes
Feedback process	Simple iterations	Method of Successive Averages	Method of Successive Averages	Method of Successive Averages
Convergence check (examples)	• VMT for iteration *n* within 5% of VMT for iteration *n 1* • 95% of links with volume change less than 5% between iterations • Relative gap < 0.001	• VMT for iteration *n* within 1% of VMT for iteration *n 1* • 99% of links with volume change less than 5% between iterations • Relative gap < 0.0001	• VMT for iteration *n* within 5% of VMT for iteration *n 1* • 95% of links with volume change less than 5% between iterations • Relative gap < 0.0001	• VMT for iteration *n* within 1% of VMT for iteration *n 1* • 99% of links with volume change less than 5% between iterations • Relative gap < 0.00001

11.1 Feedback Process Description

Highway travel times are among the important inputs to the trip distribution and mode choice components. Travel times are affected by traffic volumes as higher levels of congestion reduce speeds. The highway assignment process that estimates volumes, however, occurs after trip distribution and mode choice in the modeling process, and so highway travel times are therefore among the outputs of the highway assignment process. This means that the traffic volumes and their effects on speeds are unknown when these components are run initially, and the travel-time outputs from highway assignment may be inconsistent with the inputs to distribution and mode choice.

The initial travel times are estimated through the network skimming process as described in Section 10.3. These initial estimates may be "free-flow" times or may be based on approximated levels of congestion. In many regions with relatively low levels of congestion, these approximations are sufficient to produce reasonable model results and are consistent with the output speeds from highway assignment. In regions with higher levels of traffic, however, a process is needed to ensure consistency between travel-time inputs and outputs.

The process for travel-time feedback can be summarized as follows:

1. Run the entire model process from trip generation through highway assignment ("iteration 0"). Transit assignment may be omitted in this initial iteration.
2. Skim the highway network to produce TAZ to TAZ travel-time inputs for the next iteration.
3. Rerun the model from trip distribution through highway assignment, using the travel-time inputs from Step 2.
4. Perform convergence checks (see Section 11.3) on the model results.
   - If convergence has been achieved, produce the final model results using the appropriate averaging method (see Section 11.2). Transit assignment should be performed at this time, and the process is terminated.
   - If convergence has not been achieved, compute travel times for the next iteration by skimming the highway network and using the appropriate averaging method, and return to Step 3.

The averaging referred to in Step 4 is discussed in Section 11.2, and the criteria for determining convergence are discussed in Section 11.3.

11.2 Averaging of Information from Feedback Iterations

While it is possible to simply use the output travel times from one iteration as inputs to the next, an efficient means for achieving convergence is to average times from the various iterations. This section describes two basic ways to feed back travel times.

- Simple iterations, in which the levels of service predicted in one iteration are used without modification as inputs to the next iteration, and the results of the final iteration are accepted as the final estimate of both trips and travel times; and
- Averages of iterations, in which the intermediate trip predictions of the simple iteration process are averaged to provide the final estimate of trips, and/or the impedance variables for the current iteration are those which are consistent with average values of the trips predicted in all prior iterations.

11.2.1 Feedback Based on Simple Iterations (No Averaging)

The simplest way to perform feedback is to use the estimated travel times from the previous iteration as inputs to the current iteration. The estimates of the trips and travel times provided by the final iteration are taken to be the final estimates. If this strategy is successful, the travel-time inputs and outputs for the final iteration will be nearly the same. Also, the estimated trips for the last two iterations will be nearly equal.

The main potential problem with this strategy is that the process is not guaranteed to converge. This can occur because oscillations may cause a new iteration to be worse, in some sense, than any of the previous iterations. Even if the process does converge, it may happen slowly, resulting in high execution times. More generally, the number of trips in the final estimate bears no direct relationship to any of the paths computed in the intermediate iterations.

11.2.2 Feedback Based on the Average of Successive Iterations

A logical enhancement to the simple iteration strategy can provide a more stable process. Each of the iterations of the revised process is exactly the same as in the previous strategy. The final estimates, however, are different. Rather than using the final iteration without modification, a weighted average of the trip estimation results for each iteration is used. This averaging process occurs at the network link level. The final travel times are then obtained using the average link volumes as inputs to volume-time functions.

There are some potential problems with this strategy. Iterations with relatively low speeds will have low trip totals and therefore reduced influence on the final estimate. Again, the process may not converge, and even it does, it may happen slowly. Furthermore, the consistency of the final estimate is not guaranteed; it will surely be better than in the simple iteration strategy but may be far from the desired level. These problems can be mitigated by the use of "successive averages."

To address this issue, a process can be used where each iteration begins by estimating a new trip table based on the travel times output from the previous iteration. These trips are then assigned to new paths in the transportation networks. The results of this assignment, plus the prior iteration assignment, are then used to compute a fraction to be applied to the new trips and assigned volumes. This fraction, with the prior iteration trip table and assignment results and the new trips and assignment results computed in the current iteration, is then used to provide new "successive average" assigned volumes. Finally, these new assigned volumes are used to update all travel times.

The final estimates of trips and travel times are equal to the predictions in the final iteration; in this case, however, the link volumes in the final iteration represent a successive average. Successive averages of trips serve to dampen the oscillations of the simple iteration strategy. There are several ways to compute the fractions for each iteration. In the "method of successive averages" (MSA) [63], the fraction for iteration n is equal to $1/n$. Another way to compute the fractions is to use the network equilibrium assignment method, which computes optimal factors for each iteration to satisfy an objective function. This is known as the Evans algorithm [64]. Both of these methods ensure that this strategy converges to a stable final estimate of trips and travel times.

The MSA procedure uses the average of the link flow variables from all previous solutions so that the output of the next solution produces convergent variables. In each solution, each of the previous solutions is weighted equally. The first solution is a standard run of trip distribution, mode choice, and traffic assignment steps. The second solution starts with the travel costs of the first solution, and then is equally averaged with the first solution. The third solution, which is based on the average of the first two solutions, is weighted one-third and the former solution is weighted two-thirds. Similarly, the *n*th solution, which is based on the result of solution (*n*-1), is weighted (1/*n*) and the former solution is weighted (*n*-1)/*n*. The link volumes resulting from this method are mathematically guaranteed to converge for any pattern of highway assignments.

In regions where feedback is employed, it is considered **acceptable practice** to use feedback based on simple iterations and **recommended practice** to use the MSA procedure for averaging results from feedback iterations.

11.3 Convergence and Checks

There is no single method of checking convergence of feedback loops that is considered best practice in travel modeling. Generally, the outputs of a feedback iteration are compared to the values of the same outputs from the previous iteration, and if the differences are lower than the values set by the convergence criteria, the feedback process ends.

There are several different types of model outputs that can serve as the basis for convergence checks. These include:

- Travel times (or skim matrices);
- Trips, or trip tables; and
- Highway volumes, perhaps using an aggregate measure such as VMT.

The comparisons may be based on a straight comparison of an aggregate statistic. For example, if the VMT in iteration *n* is within five percent of the VMT for iteration *n-1*, the model may be considered converged although VMT checks alone are considered an insufficient convergence measure. Another aggregate statistic that is sometimes used is relative gap, the same statistic used to determine whether an equilibrium assignment has converged (see Section 10.1.1). For disaggregate statistics (e.g., trip tables or skim matrices), a measure such as root mean square error (RMSE) (see Section 10.5.2) may be used. In these cases, convergence is determined when the RMSE between the results of successive iterations goes below a set value. Another measure used in some areas is the change in link volumes, where convergence is assumed when the percentage of links with volume changes above a certain threshold (say, five percent) between iterations is lower than a set amount (say, one percent). Another method proposed by Slavin [65] is the "skim matrix root mean square error." This metric measures the difference between skim matrices in adjacent feedback loops. As convergence is reached, the difference between the skim matrices should decrease, indicating increasing stability between loops. The use of both this metric and the relative gap convergence method for traffic assignment creates a fixed point solution for the travel demand forecasting problem.

If relative gap is used as the convergence criterion, recent research indicates that a very small value such as 0.00001, should be used to achieve sufficient convergence. Some areas, though, have used a larger threshold, such as 0.0001 or even 0.001. Obviously, the tighter the criteria, the longer the potential processing time to obtain. The trade-offs between greater stability in results and longer times spent running the models should be considered as model approaches are developed.

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CHAPTER 12. DOCUMENTATION AND DELIVERABLES

This chapter discusses the policies for providing documentation and deliverables for model validations and updates in Virginia. Because model documentation is produced at the end of the model update process, when resources and time might be tight, there is often pressure to produce it quickly, and perhaps not as comprehensively, and not to review it thoroughly. However, good and complete documentation is essential for proper understanding by model users and important for informing interested parties on how model processes function during model applications and reviews. Quality control for model documentation and all deliverables is therefore critical.

12.1 Model Documentation

Model documentation should provide complete information on the model development, validation, and calibration processes. The following items should be included in model documentation reports:

- Introductory/summary information, including the motivation for the model update and the specific areas in which the model was updated and a description of the report's organization;
- Data used in the model update, estimation, and validation (the types of data items discussed in Chapter 3 of this manual);
- For each model component, specifics of the model estimation, transfer, or assertion results, including details of all assumptions, model parameters, and estimation statistics (if applicable); and
- Complete documentation of the validation of the model, including the validation of all components.

The documentation report for any model updates should be presented to VDOT in hardcopy and electronic format as specified by the VDOT designated modeler.

12.2 Model Deliverables

Besides the model documentation, other model deliverables that should be provided for every updated model include the following:

- Data files used to develop the model, including survey data sets and model estimation files;
- Data files used in model validation;
- All model input data files, including highway and transit networks and socioeconomic data files;
- Other associated files such as a shape file with the TAZ boundary information;

- All files necessary to run the model in the modeling software platform;
- Source code for any programs developed to run the model;
- Model output files for the validated base-year scenario and other scenarios used in model testing and validation; and
- Any reports showing model output results for the validated base-year scenario and other scenarios used in model testing and validation.

Table 12.1 shows a checklist of the files that should be provided to VDOT at the conclusion of model improvement projects. Survey data files (Items 2 through 5 in Table 12.1) should include all applicable files (for example, household file, person file, trip file, etc.) and should include the geocoded data.

Table 12.1 Checklist of Deliverables Needed for Model Improvement Projects

Item	Deliverable	Description
1	TAZ Structure	Shape file
2	Travel Survey	In a database format as directed by the VDOT designated modeler
3	External Station Survey	In a database format as directed by the VDOT designated modeler
4	Transit On-Board Survey	In a database format as directed by the VDOT designated modeler
5	Other Survey Results	In a database format as directed by the VDOT designated modeler
6	Transportation Networks (Highway, Transit)	Network file in modeling software version currently used in Virginia
7	Land Use Data Files for All Tested Scenarios	In a database format as directed by the VDOT designated modeler
8	Traffic Count Data (including counts of external stations)	In a database format as directed by the VDOT designated modeler, with a correspondence to the transportation network.
9	Required Model Execution Files	All required files for using and enhancing further model in the modeling software format.
10	Complete Software Source Code	For any software developed for the model
11	Model Results	Model output files (loaded network, trip tables, etc.) for the validated base-year scenario and other scenarios used in model testing and validation in a format compatible with the modeling software.
12	Model Documentation Report	In Word and PDF format

The deliverables shown in Table 12.1 are required unless specified otherwise by the VDOT designated modeler. The file format for model deliverables should be compatible and consistent with established VDOT practice. Model files should be delivered in a format compatible with the current modeling software used by VDOT. Model documentation files should be delivered to VDOT in both Microsoft Word and PDF format.

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CHAPTER 13. APPLICATION AND ANALYSIS

This chapter discusses the policies and procedures for developing model outputs for presentation and using model results for project planning applications.

13.1 Developing Model Outputs for Presentation

The main outputs of travel models that are used and presented by planners include aggregate statistics such as VMT and mode shares, and more detailed outputs such as link-level traffic volumes and boardings for transit routes. Modeling software has several standard reporting procedures available for reporting typical model outputs. It is also relatively easy to present model results graphically through maps.

13.1.1 Traffic Volumes

Traffic volumes at the link level are among the chief outputs of highway assignment and represent estimates of the volumes on specific roadway segments for the scenario being modeled. Because of the uncertainties and the assumptions involved in forecasting, it has long been recognized that modeled link volumes should not be treated as precise, accurate estimates of future traffic volumes. Before presenting modeled volume information or using it in planning analyses, it should be critically examined.

NCHRP Report 255 has long been used to refine model volume outputs for project analyses [62]. NCHRP has updated this report through Project 8-83, "Analytical Travel Forecasting Approaches for Project-Level Planning and Design," and a new report, *NCHRP Report 765*, was published in 2014 [66]. It is both **acceptable practice** and **recommended practice** to use the techniques in *NCHRP Report 765* to adjust model volume outputs. Section 13.3 has some discussions of procedures to refine model outputs.

An issue that should be considered when presenting model volume results is that of "false precision." The analytical techniques used in modeling provide specific estimates of traffic volumes, down to the vehicle level (or even fractions of vehicles). It is obvious, however, that there is error associated with the outputs of any model, even a well validated model. These may be forecasting errors, simulation errors, or simple reflections of the uncertainties involved in preparing forecasts. While it might be desirable to present the volume outputs as ranges, it is impossible to quantify exact error ranges – one cannot say that the volume estimate is within a certain range with, say, 95 percent confidence, and models do not output such ranges. It is therefore desirable to present results in a way that does not provide users and viewers of the results with false confidence about the precision of results. A common way of partially addressing this concern is to present volumes as rounded numbers, say to the nearest 100.

While individual link volumes can be plotted using modeling software or GIS, aggregate measures related to traffic volumes, such as VMT, are usually not displayed graphically. These are often reported from standard modeling software outputs. For measures that are used frequently, modelers may wish to create custom reports.

13.1.2 Other Measures

There are several other measures that are used in planning and project analyses that are derived from travel model outputs. These may include:

- *Highway speeds and travel times*, either at the link level or as aggregate measures such as vehicle hours traveled;
- *Transit ridership*, as route- or station-level boardings or as link volumes; and
- *Measures of total travel* derived from trip tables, including trips from one location to another and mode shares.

While a few of these measures may be plotted using modeling software functions or GIS (for example, link speeds), most of them are generated using simple reports in the modeling software or using custom reports developed by users.

The same cautions cited in Section 13.1.1 regarding the need to examine raw model results and the "false precision" of outputs apply to all model outputs. Planners should use the same care in using and presenting these model results as is used for traffic volumes.

13.2 Using Model Results for Planning Applications

As discussed in Chapter 2, there are many uses for results from travel demand models. It is important to recognize that a travel model is just one tool among many that planners can use for their analytical needs. In some cases, it may make sense to use tools other than models. This section discusses some of the common transportation planning analyses and how (and whether) models can be used in conducting them.

13.2.1 Evaluation of Transportation System Performance

Performance measures are usually somewhat aggregate in nature although some measures may be aggregations of disaggregate data (for example, percentage of roadway miles operating under congested conditions). This means that travel demand models, which can cover the entire planning region as well as providing information at the facility level, are well suited to system performance evaluations. Planners often develop custom reporting of frequently used performance measures from model outputs.

An example of using travel demand model in evaluating system performance is HRTPO's Existing and Future Truck Delay in Hampton Roads [67] (Figure 13.1), expanding the analysis of existing truck volumes and delays by location to include future truck volumes and delays in Hampton Roads. It uses the new truck component and time-of-day capability of the regional travel demand model to forecast truck volumes and congestion to be faced by trucks in the next 20 years. The report compares existing to forecasted truck delays, highlighting future roadway segments with the highest total weekday truck delays and resulting annual truck congestion costs.

Figure 13.1 Sample Evaluation of Transportation System Performance

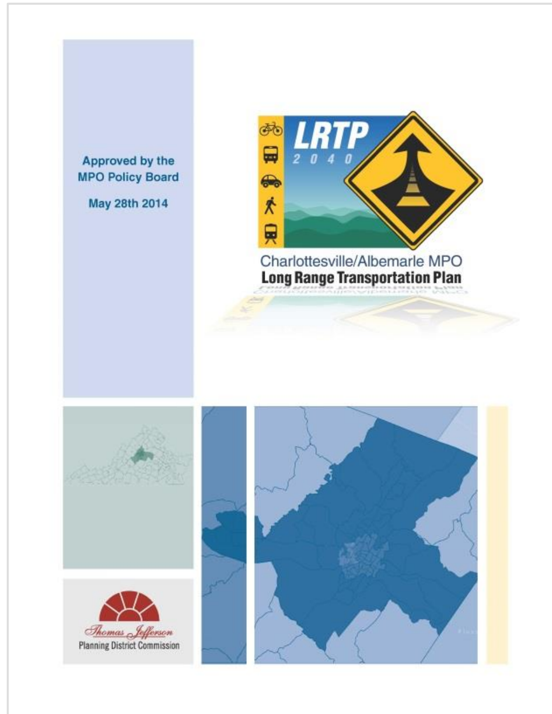
Source: HRTPO, "*Existing and Future Truck Delay in Hampton Roads*," 2013 [67]

13.2.2 Long- and Short-Range Transportation Planning

The development of long-range transportation plans involves the evaluation of sets of projects that planning agencies are considering improving mobility and the quality of life in the region. This often involves scenario analysis, where groups of projects are analyzed together to determine their cumulative impacts over the long term. Short-term plans (for example, Transportation Improvement Programs) require similar analyses although it may be desirable to estimate the impacts of some projects over a shorter timeframe. Generally, models are well suited to this type of analysis since scenarios can be created to represent individual projects or groups of projects. However, there are some types of projects (see Section 13.2.4) for which other analysis tools are more appropriate, and such projects may be included in transportation plans. In such cases, it may be best to analyze those specific projects separately using other appropriate tools.

Most MPOs in the Commonwealth of Virginia have used their regional travel demand models to assist in the long range transportation plan preparation, such as FAMPO's 2040 Long Range Transportation Plan [68] and TJPDC's 2040 Long Range Transportation Plan [69] (Figure 13.2).

Figure 13.2 Sample Long Range Transportation Planning Efforts



13.2.3 Air Quality Conformity Analysis

Many of the inputs into air quality analysis are derived from travel model outputs. These mainly are measures of demand (e.g., VMT) and travel speed, often segmented by facility type, geographic subarea, etc. Since emissions rates vary by vehicle type, the use of separate outputs for autos and trucks, and trucks by type if modeled, can be very useful. All of these measures are available from travel model outputs although they need to be examined and possibly refined or "post processed" before being used in air quality analyses. There are several other inputs into air quality analysis that are not derived from models, including climate and vehicle fleet information; these data must be developed separately.

13.2.4 Evaluation of Transportation Improvements and Infrastructure Investments

The evaluation of individual larger scale transportation projects, including highway improvements and transit service changes, also is well suited for analysis using travel demand models. Since the impacts of these projects may go well beyond their immediate vicinity, models can be used to examine these more distant impacts.

There are some types of projects for which models may not be as well suited for analysis. These include:

- *Traffic operations analyses* – Highway networks in conventional travel demand models do not represent all aspects of roadway design; lane configurations, turning lanes, parking allowances and prohibitions, and merging/weaving sections are not explicitly specified. The static highway assignment procedures used do not account for vehicle interactions such as intersection dynamics, queuing, etc. Microscopic or mesoscopic traffic simulation models are better suited for such analyses. While regionwide traffic simulation is not yet practical in most cases, it is common to use outputs from travel demand models as inputs to traffic simulation tools. Traffic operations software also can be useful for these analyses.

- *Provision of travel information* – Projects concerning the amount of information provided to travelers and the way in which it is provided may include installation and operation of variable message signs; provision of information through on-line sources, smartphones, and similar means; and traveler information services such as 511 services. Because travel demand models do not use as inputs measures of the information that travelers have, such projects cannot be analyzed using these models. It is likely that data specific to the type of information provided and its effects on travel behavior will need to be collected although there are studies, such as FHWA's Integrated Corridor Management project, that are looking into this topic.
- *Dynamic pricing* – Some types of toll facilities and managed lanes have dynamic pricing that changes by time of day depending on traffic levels. While toll roads can be analyzed in travel models, prices that vary during the day cannot be accurately analyzed because of the lack of a time-of-day choice component. Activity-based models do have this capability, but some of the mechanisms by which dynamic prices are set have not been incorporated into the type of highway assignment procedures used by both conventional and activity-based models.
- *Transportation demand management (TDM) actions* – Many of these types of actions, such as telecommuting, compressed work weeks, and carpool matching, are not well suited to analysis by travel models. In practice, such policies have been analyzed using post-processing techniques, sketch planning analyses, or data-driven tools.

13.2.5 Evaluation of the Effects of Transportation and Planning Policies

Some types of planning policies are well suited to analysis using travel demand model outputs. Toll roads can be analyzed in terms of their effects on mode and route choice although, as noted above, dynamic pricing may be difficult to analyze. Other types of pricing policy analysis, such as parking pricing or gasoline price (or tax) changes, also can be modeled. Land use policy analysis may be difficult to perform using conventional travel models because of the limited nature of the land use-related policy variables that are used in model inputs and the relatively coarse level of spatial detail in models. Activity-based models may be better suited, especially if parcel-level land use data are used. Some transit-related policies may be able to be modeled although the way in which pricing is represented – average fares by aggregate population segment, without explicitly modeling pass usage – limits the types of policies that can be accurately analyzed.

13.3 Model Applications for Subarea and Corridor Analysis

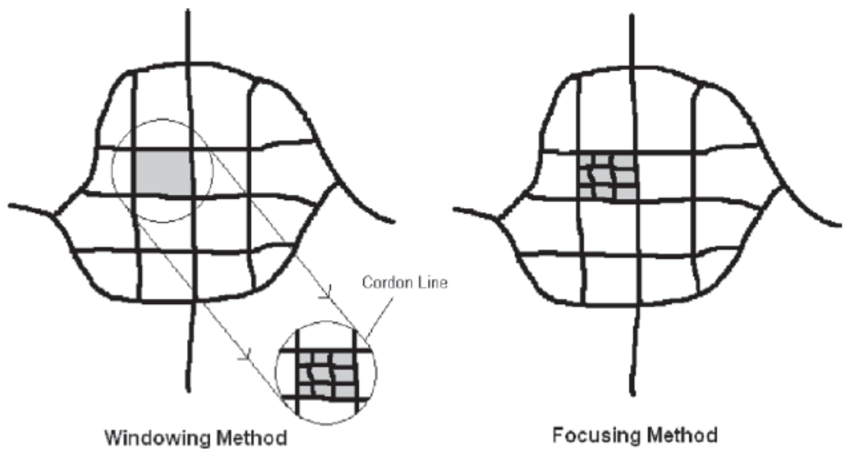
Regional travel demand models are often used to support subarea planning studies such as Comprehensive Plans, Transportation Plans, and Transit Development Plans at the County and sub-county levels, and to support the corridor level transportation improvement projects in their different stages of life cycle from the initial project planning and programming, to preliminary design and environmental studies, to final design, constructions, and operations. While these model applications are well-established uses of regional travel demand models, it is a good and **recommended practice** to tailor or refine the regional travel demand models to make the models better suited to these applications, as the regional models are typically calibrated and validated at the regional level and its validity at the subarea and corridor levels is not necessarily established during the regional model development process. This section focuses on providing guidance in choice of analytical methods, use cases (applicability situations), procedures and validation metrics.

13.3.1 Analytical Methods

One key component of refining the regional model is to refine the spatial detail of a regional model to make it achieve reasonable validity at the subarea and corridor levels. Three basic types of subarea analysis methods, focusing, windowing, and custom applications, are discussed in NCHRP report 765, *Analytical Travel Forecasting Approaches for Project-Level Planning and Design* [66]. Configuration of custom applications varies a great deal in terms of the level of spatial details, employed modeling techniques as well as type and accuracy of results to meet special study needs. The subarea analysis in this policy document focuses only on focusing and windowing methods although some special topics are addressed as well.

The windowing approach essentially extracts the subarea under the study from a regional model and sets it up as a stand-alone subarea model. In contrast, focusing involves enhancing the subarea under the study in terms of model inputs and components, leaving the rest of the modeling domain intact, but performing modeling analysis for the entire region of the travel demand model as illustrated in Figure 13.3. Focusing and windowing methods are also different in several other ways as summarized in Table 13.1.

Figure 13.3 Illustrative Example of Subarea Focusing and Windowing Methods



Source: CDM Smith, et al., "Analytical Travel Forecasting Approaches for Project-Level Planning and Design, NCHRP Report 765," 146, Figure 7-1, 2014 [66].

Table 13.1 Focusing and Windowing Methods

Features	Analysis Methods	
	Focusing	**Windowing**
Spatial dimension	Focus area varies, with a regional context	Small area
Temporal dimension	Short, intermediate, and long	Short
Spatial detail for subarea	Enhanced	Enhanced
Temporal detail	Typically, time periods of day	Peak hours
Extraction of subarea	No	Yes
OD trip table	Regional	Separate OD trip tables for subarea only
Other details, e.g. traffic operational characteristics	Limited	More flexible to add
Interaction between subarea and rest of region	Maintained	No/Limited
Consistency with regional model in traffic assignment method and parameters	Maintained	Preferred but not necessary
Model run time	Similar to regional model	Much shorter

13.3.2 Use Cases (Applicability Situations)

The choice of methods between focusing and windowing depend on user cases (Table 13.2) and considerations of major determining factors, which may include the following:

- Goals and objectives of the study. If the study involves evaluations of policies, programs, and projects that have significant regional implications in the areas outside the study area, it is **recommended practice** to use the focusing approach to modeling, which will maintain the interactions between the study area and the rest of the modeling domain. On the other end of this continuous spectrum of regional significance, if the study is intended to analyze the impacts of policies, programs, and projects that tend to be localized and limited, it is **acceptable practice** to use the focusing or windowing method.
- Types and dimensions of analyses. The focusing method is applicable to a broad range of analyses in terms of analytical time horizons, study area geography, and analysis types, while the windowing method is best suited to support the analyses with a small area, limited and localized impacts, short time horizons, especially traffic operation analyses.
- Computational efficiencies. One of the original motivations for using the windowing approach is its advantage in the computational efficiencies in terms of model run time that is much reduced from running the entire regional model. With rapid advances in computing capabilities, computational efficiency is now only a minor consideration.

Table 13.2 Model Applications Use Cases and Analytical Methods

Use Cases	Acceptable		Recommended	
	Small	**Large**	**Small**	**Large**
County- or City-wide planning studies such as Comprehensive Plan, Transportation Plan, Transit Plan	Focusing	Focusing	Focusing	Focusing
Subarea planning studies at the subcounty level	Focusing	Focusing, Windowing if small and localized	Focusing	Focusing
Growth scenario analysis at jurisdiction, subarea, and corridor level	Focusing	Focusing	Focusing	Focusing
Corridor studies (corridor of regional significance)	Focusing	Focusing	Focusing	Focusing
Corridor studies (corridor of local significance)	Focusing, Windowing	Focusing, Windowing	Focusing	Focusing
Local roadway projects	Focusing, Windowing	Focusing, Windowing	Focusing	Focusing, Windowing
Traffic operation analysis	Focusing, Windowing	Focusing, Windowing	Focusing, Windowing	Focusing, Windowing
Traffic forecasting to support Micro-Simulation at a corridor level	Focusing, Windowing	Focusing, Windowing	Focusing, Windowing	Focusing, Windowing

13.3.3 Procedures

Model applications in subarea and corridor analysis generally need to address several essential elements which are critical to achieve the validity needed for such analyses. Different use cases may have different levels of needs and/or requirements for these essential elements, while different approaches (focusing and windowing) may have a few minor differences. The following discussion focuses on subarea definition, refinements of TAZ system, enhancements of transportation network, preparation of other model files, and validation.

1. Define subarea

A subarea is sometimes well-defined in some planning studies such as county- or city-wide planning studies, or a sector planning study below the jurisdiction level. In other situations, a subarea area needs to be defined in accordance with the federal and state regulations and guidelines such as National Environmental Protection Act (NEPA) regulations. In general, the subarea should:

- Cover the areas that should be broad enough to encompass the entire area in which the project under the study has the potential to cause direct and/or indirect effects; the area with direct effects may be smaller for developing project alternatives than the area with indirect effects.
- Include the portion of highway network that impacts and is influenced by the traffic carried by the project alternatives analyzed. If the project alternatives are within a congested portion of the region, the subarea should be larger than it would need to be if the project were within a lightly traveled portion of the region. Select link/zone analysis using the roadway segments and TAZs in the vicinity of the project alternatives may be performed to assist the delineation of the project impact area.
- Be defined as a contiguous set of regional-model TAZs to help with land use data transferring.
- Keep the boundary convex to minimize the chance of a single vehicle path entering/exiting the subarea more than once.

When windowing method is applied, additional caution needs to be exercised to balance the study needs and required efforts to prepare the subarea model.

2. Refine TAZ system

Subarea modeling is always motivated by the provision of more spatial detail and more accurate measures of effectiveness than can be offered by the regional model. Refining the TAZs in the subarea can increase the spatial accuracy of land use activities, improve the representation of traffic access to local transportation systems, and enable better evaluation of land use impacts on travel demand, especially some of those microscopic effects of land uses. The decision to refine the TAZ system in the subarea should be based on review and evaluation of the ability of the existing TAZ system to meet the needs of the subarea study.

- Refining TAZs within the subarea generally takes the approach of subdividing the original TAZs into smaller subarea TAZs, usually about the size of one or a few city blocks. Reconfiguring the TAZs, i.e., splitting original TAZs and merging them into different configurations that cross the boundary of original TAZs, should be avoided unless justified on special considerations.
- Recommendations included earlier in this policy document for delineating TAZs for regional model also apply to subarea modeling (Section 4.1.1).
- To the extent possible, the land use in subdivided TAZs need to be homogeneous.
- Subarea TAZs should be used to introduce better resolution to isolate the major activity centers with high density of population and employment from relatively less dense mixed-use developments within the subarea.
- For a development site, a zone should be a single parking lot or the area of a large parking lot that is served by a single exit/entrance.

- Demographic and land use data need to be obtained from local planning agencies or developed through disaggregation of the original TAZ data based on land use activities within each subarea TAZ, using more spatially detailed data including parcel data.
- The correspondence between the TAZs in the regional model and the subarea model needs to be developed to assist in disaggregating the trip tables to accommodate revised/subdivided TAZs.

Both TransCAD and Cube use the correspondence table that includes trip disaggregation factors to disaggregate trips tables. The disaggregation factors should represent the share of travel demand in the subdivided TAZs from the original TAZ. Usually the share of weighted total of population/households and employment is a good proxy for the share of travel demand.

3. Enhance transportation network

Enhancing the transportation network is another important and essential aspect of subarea modeling and analysis. Although an adequate level of highway network detail to be included in the subarea model is analysis specific, it should include the following considerations, with the first seven points applicable to both focusing and windowing methods.

- The network within the subarea should be as detailed as practical, including all arterial streets, collectors, and any higher functional class roadways. Certain local roads and driveways from parking lots may be needed for continuity purposes and TAZ subdivision.
- The model network within the project impact area should be checked for connectivity, directionality, and turn penalties to make sure all vehicle movements are properly represented.
- Centroids and centroid connectors must be created and adjusted for each external station and each TAZ within the subarea to represent the traffic loading patterns.
- Key highway network attributes—for example, facility type or functional class, use restrictions, number of lanes, post speed or free-flow speed—need to be reviewed and refined.
- Turn prohibitions and penalties need to be reviewed and refined for those intersections under study, especially when turning movements are used for intersection analysis.
- When intersection modeling is involved, network attributes representing intersection characteristics need to be reviewed and refined, including intersection types and turn lanes.
- Transit network representation needs to be reviewed and refined to make it consistent with the refined highway network in the subarea, including stop locations and routing alignments.

- For the focusing method, the network outside the subarea can be prepared by either keeping the network from the regional model intact or simplifying the regional network. The simplification approach was historically motivated by the benefits in computational efficiencies, but due to rapid advances in computational power, these benefits have diminished and may not justify the associated cost.
- The windowing method may require the review of additional network attributes. The subarea model using the windowing method may use different generalized cost specification and Volume-Delay Function to benefit from enhanced modeling sensitivity to additional traffic operational factors, e.g., signal timing/phasing, number of turning lanes, turn prohibition, and on-street parking.

4. Enhance model functionality and prepare other model files

In addition to the spatial enhancements in terms of TAZ and network representation, temporal enhancements are sometime necessary, e.g., to use separate assignments of a peak hour and shoulder hours (pre-peak and post-peak hours) to replace peak periods.

For studies with a primary objective of evaluating congestions and intersection operations, it would be necessary to enhance the model's capability to model delays. Ideally, intersection delay should be incorporated into the subarea modeling process, with detailed representation of intersection characteristics such as turn lanes and signal timing.

The windowing method extracts the network using the subarea boundary and develops compatible trip tables. The subarea extraction procedure in Cube/Voyager and TransCAD automatically creates the following:

- **Subarea model network**
    - All network links, including centroid connectors, within the subarea remain the same as in the regional model network. The original zones in the subarea become the internal TAZs for the subarea model.
    - Network links with both endpoints located outside the subarea are removed.
    - Network links crossing the subarea boundary are converted to centroid connectors with the endpoints located outside the subarea converted to external stations.
- **Subarea trip tables**. An O-D trip table will be created for each mode/vehicle class used in traffic assignment.

The windowing method also requires that traffic counts, which could include truck counts and period level counts depending on study needs, must exist on every link crossing the sub-area boundary.

One key component for the windowing method is to develop trip tables using a procedure of Origin-Destination Matrix Estimation (ODME). ODME utilizes the traffic count data to mathematically derive the "most likely" O-D pattern based on a defined objective function, the allowable range of deviation from the seed matrix values, as well as used traffic routing algorithms (e.g. UE and DTA). The effectiveness of ODME and the credibility of results are limited by the number of ground traffic counts and the size of O-D matrix for adjustment, which collectively defines the degree of freedom of the mathematical optimization problem to be solved.

The windowing method significantly reduces the degree of freedom and hence improves the effectiveness and credibility of ODME. For instance, a subarea model using the windowing method with 10 internal and 5 external TAZs have only 225 O-Ds to adjust, as opposed to 640,000 for a regional model with 800 TAZs. As a result, ODME is **not** recommended for model calibration at a regional level at which focusing operates. Modeling software, e.g., TransCAD and Cube through separately licensed Cube Analyst, allows the user to specify constraints to limit the 'freedom' when estimating O-D. However, identifying O-Ds to apply limits is often too challenging to justify the benefits.

ODME requires many assumptions and often lacks behavioral underpinnings, even under the windowing environment. It is more suited to a short-range, small area study than a long-range, large area study. Users of ODME should give careful considerations to the choice of specific ODME techniques and algorithms, their assumptions and parameters, statistical measures of ODME reliability, and input data that are required.

Two major inputs to the ODME process are traffic counts and seed O-D table. The windowing method is typically used for a peak hour or peak period, and thus traffic counts should be bi-directional and by time of day. Turning movement counts may also be an input, depending upon the software algorithms for the ODME estimation. The quality and locations of the traffic counts are critical for the ODME process and results and should be reviewed carefully to gain a good understanding of the magnitude of errors in traffic counts data. It is desirable to assign weights to all counts to emphasize those counts of greatest reliability, such as those from continuous counts locations. A target value for the amount of deviation between the traffic counts and the estimated traffic volumes should be set no lower than the amount of error in a traffic count. Rules have been proposed for preparing traffic counts to support an optimal ODME estimation. Based on the O-D covering rule, at least one traffic count must be located on the path(s) between every O-D pair in a study network [70]. In other words, for the route(s) connecting each O-D, there must exist at least one link with a traffic count. Link independence rule states that the traffic counts on the study network should be linearly independent.

A seed O-D table is important as it represents travel behavior in the study area and can come from different sources, including:

- Surveys, e.g., a cordon survey, which can be time-consuming and expensive;
- Vehicle re-identification methods, which include Bluetooth detectors, aerial surveillance, cell phone tracing, and license plate matching and may be expensive and time-consuming;
- Big data, such as StreetLight O-D data, which may include those based on location-based services and GPS, as discussed in Section 4.2.2;

- Travel demand models, which can provide estimated trip tables that are based on modeled travel behavior; and
- Assumptions about driver behavior within small areas, in terms of minimizing turns.

It is desirable to set a reasonable amount of control for the degree of deviation between the estimated flows and seed flows, depending on the confidence on the seed OD flows. This serves two purposes, one to preserve the behavioral patterns in the seed OD table to the extent that is consistent with the confidence level, and the second to avoid the over-fitting to the traffic counts which have underlying errors. The results of the ODME must be reviewed in terms of deviations from the seed OD table to evaluate the magnitude of distortions. The average trip length for the estimated OD table should be computed and should not differ significantly from the average trip length of the seed OD table.

5. Subarea model calibration and validation

Validation of the subarea model is necessary to demonstrate the validity of model performance in the subarea so as to ensure it can be used for subarea studies that it is intended to support. The general validation procedures and guidance discussed in the previous chapters are applicable to the subarea model validation, especially those based on the focusing approach to subarea modeling, while there are some special considerations for the windowing approach.

The objective of a subarea modeling is to enhance the model's validity to an adequate level so that it can be better suited to support technical evaluation of projects, policies, and programs at the subarea level. With enhanced representation on both the demand and supply sides, the model should theoretically perform better than the original regional model, at least from the travel behavior perspective. However, it does not necessarily translate to better validation metrics in the subarea. Efforts need to be made to fine tune the model to achieve better performance in a subarea.

- In general, a wholesale calibration and validation of the regional model is not warranted unless the regional model does not meet the special requirements of a project study. For example, the FTA has special requirements for New Starts ridership forecasting, and after the initial review of the regional model, it may be determined that the regional model may need major changes in the mode choice model and associated components. As a result, a re-calibration and validation is warranted.
- In many cases, validation is mostly focused on improving the model performance in trip assignments in the subarea while it is also necessary to conduct reasonableness checking and validation for model components before the trip assignment.
- It is often necessary to define cutlines and/or screenlines for the subarea in order to better evaluate the model performance.
- Adjustments of network link attributes like speeds or capacities, which are often used in practice, may be justified in the subarea; in many cases, these adjustments should be moderate while caution should be exercised with severe adjustments.

- Adjustments should be kept to a minimum and employed mainly as a tool for fine-tuning validation of the assignment process;
- A logical hierarchy of free-flow speeds should be maintained (e.g., higher speeds on freeways than arterials);
- Mode choice and trip distribution results should be reviewed to ensure that speed adjustments have not caused the balance of highway and transit speeds to be significantly impacted; and
- Resulting congested speeds should be reviewed for consistency and reasonableness.

- Addition of screenline/cutline penalties or K factors, while generally discouraged in practice, may be necessary to improve the trip distribution patterns in some special situations where there exist real or perceived barriers such a river crossing or a state line.

Data that are used to support subarea model validation are mostly similar to those used for the reginal model validation. However, special attention should be paid to the spatial and temporal details of these data and their accuracy to meet the subarea model validation needs.

- **Traffic counts and transit ridership**. Traffic counts need to be collected for as many network links in the study area as possible, particularly for those critical links that are used by most O-D paths. Simple shortest path highway assignment using a trip table that contains one trip per O-D provides good estimate how many O-D paths use a link in the network. Traffic counts need to be reviewed carefully for their locations as traffic counts reported in the VDOT publications often cover a long roadway where several model links are involved and volumes may vary considerably by roadway segments/links. In addition, the quality of counts (AADT and AAWDT) should be considered in the validation process with more weights given to the higher quality counts; VDOT counts data publications include quality codes with the highest quality being complete continuous count data. Turning movement counts are useful for checking reasonableness of turn volume estimates from a model, especially when an intersection analysis is desired for the study area. Turning movement counts are often collected for project-level studies, on a typical 24-hour or 48 hour basis. The inherent variations in these types of short-term counts need to be recognized.
- **Travel time and speed**. Some subarea studies may require good estimate of travel speed and time. For calibration, travel speed and time data can be either collected using conventional methods such as floating-car method and Bluetooth technology, or most recently from Big Data sources, e.g. NPMRDS, INRIX, HERE and StreetLight. For a detailed discussion of the speed and time data, see Section 4.2.4.
- **O-D patterns**. A focused review of O-D pattern for the study area helps identify any significant bias towards the estimated trips entering and leaving the study area. Biased OD patterns may misinform and undermine the highway network review and validation effort. O-D data for a relatively small area can be collected using Bluetooth technology, or from Big Data products such as StreetLight and AirSage.

The types of validation metrics for subarea model validation are generally similar to those used for regional model validation. The accuracy of validation metrics should receive special attentions.

- The validation of a subarea model should make validation metrics achieve the level of accuracy that serves the intended goals and objectives of a subarea study well. In other words, the validation requirements vary with the needs of a subarea study, which can vary considerably. For example, a county-wide planning study generally would have a less stringent requirement for validation than a corridor study or forecasting in support of microsimulation.
- While there are no well-established standards for subarea model validation, the regional model validation guidance in Sections 10.5 and 10.6 (Tables 10.3, 10.4, 10.5 and 10.6; Figures 10.1 and 10.2) should be applicable to the subarea model validation as the minimum consideration.
- In many cases, traffic volume forecasts by time of day, especially for peak hours, are critically important for project-level studies, making it essential to conduct validation check based on directional and time period traffic counts when data are available. In these cases, validation guidance by volume groups is most applicable (as shown in Table 10.5).
- The maximum desirable deviation curve established for Virginia regional model validation as shown in Figure 10.2, which is more stringent than the NCHRP 255 curve, is applicable to many subarea modeling use cases such as County-wide planning studies.
- It is reasonable to expect more stringent validation metrics for the corridor level studies as exemplified by the guidance on volume deviation and screenline/cutline deviation for corridor validation in Florida (Tables 13.3 and 13.4).
- It is also reasonable to expect more stringent validation metrics for the subarea model that serves the microsimulation model. Another VDOT policy document (TOSAM), "Traffic Operations and Safety Analysis Manual," establishes several model calibration thresholds for micro-simulation model as in Table 13.5 [71]. These measures are based on hourly traffic volumes for links and/or turning movement, and a select number of critical links and/or turning movements in the microsimulation area. When compared on a daily volume basis, these thresholds are generally more stringent than maximum desirable deviation curve for cutline/screenline in Figure 10.2. Table 13.5 can be used as a reference for subarea model validation when serving the needs of operational analysis and microsimulation, while recognizing that the subarea travel demand model may not have the detail and sophistication to achieve the level of accuracy that is required when conducting a microsimulation.
- Caution needs to be excised to avoid over-fitting to the traffic counts which have substantial errors, especially those short-term counts. The FHWA report *Calibration and Adjustment of System Planning Models* illustrates this point clearly, using the maximum desirable deviation curve from the NCHRP 255 report superimposed with another curve to represent count errors, as rendered in Figure 13.4 from the NCHRP 765 [66].

It argues that a perfectly-calibrated model should have about one-third of the points fall above the count-error curve and about two-thirds of the points fall below the count-error curve. A validation performing better than this is likely to simply replicate the error in the traffic counts rather than the true levels of traffic.

- Table 13.6 summarizes the validation metrics that are generally used in the subarea studies, and the guidelines for these validation metrics should vary with the intended goals and objectives of subarea studies. Generally, the validation targets are similar to regional model validation when serving the needs of a planning study in a large subarea that typically uses a focusing method, but they are more stringent in support of operational analysis and microsimulation, which usually uses a windowing method. Table 13.7 shows percent root mean square error (RMSE) guidelines for subarea and corridor analyses, a variation of Table 10.5 with more categories and more stringent guidelines, especially for studies to support operational analysis and microsimulation.

Table 13.3 Volume Deviation Guideline for Corridor Validation (FSUTMS)

	Deviation of Estimated Volume from Observed Counts	
Statistics	**Acceptable**	**Preferable**
Freeway Volume-over-Count	+/- 6%	+/- 5%
Divided Arterial Volume-over-Count	+/- 10%	+/- 7%
Undivided Arterial Volume-over-Count	+/- 10%	+/-7%
Collector Volume-over-Count	+/- 15%	+/-10%
One-way/Frontage Road Volume-over-Count	+/- 20%	+/-15%

Source: Cambridge Systematics, Inc., "Final Report, Model Calibration and Validation Standards, FSUTMS-Cube Framework Phase II," 2-30, Table 2.15, 2008 [61].

Table 13.4 Screenline/Cutline Validation Guidelines for Project Forecasting

Type	% Deviation
External Model Cordon Lines	0%
Screenlines/cutlines with greater than 70,000 AADT	+/-5%
Screenlines/cutlines with 35,000 to 70,000 AADT	+/-10%
Screenlines/cutlines with less than 35,000 AADT	+/-15%

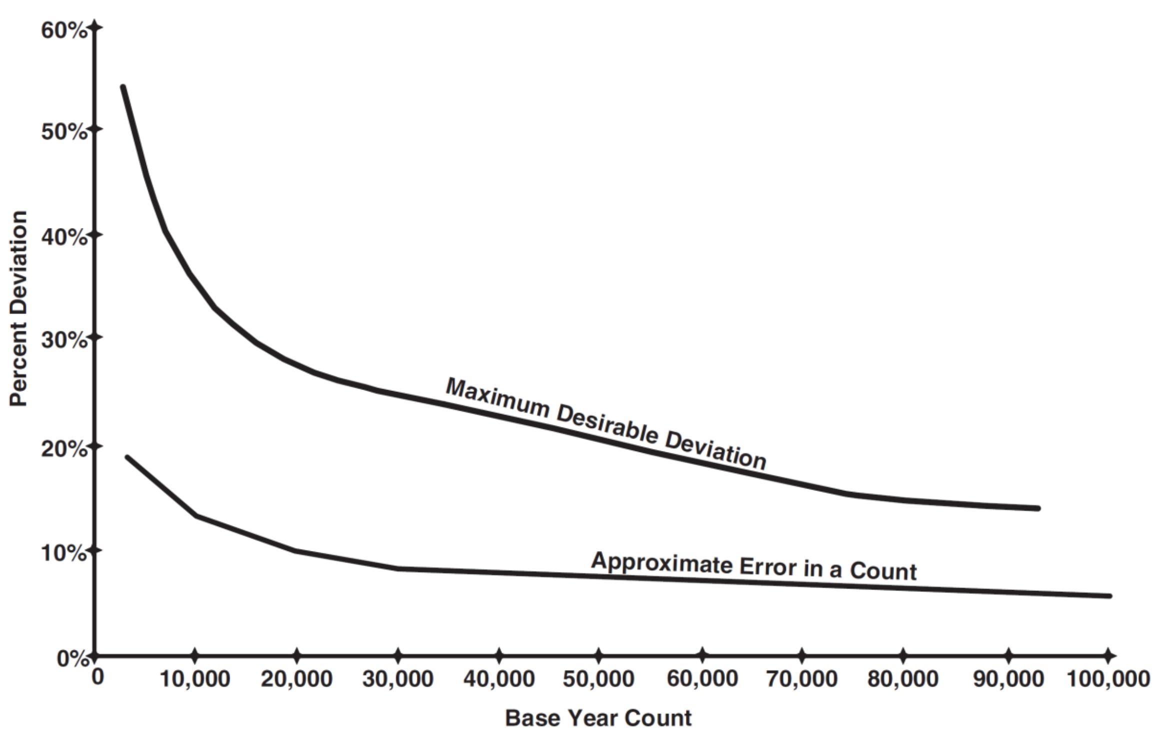
Source: Cambridge Systematics, Inc., "Final Report, Model Calibration and Validation Standards, FSUTMS-Cube Framework Phase II," 2008 [61].

Table 13.5 VDOT TOSAM Microsimulation Model Calibration Thresholds

Simulated Measure	Calibration Threshold
Simulated Traffic Volume (vehicles per hour) 85% of the network links and/or turning movement, and a select number of critical links and/or turning movements, as determined by the District Traffic Engineer (DTE) or his/her designee, shall meet the calibration thresholds.	Within ± 20% for <100 vph Within ± 15% for ≥100 vph to <1,000 vph Within ± 10% for ≥1,000 vph to <5,000 vph Within ± 500 vph for ≥5,000 vph The traffic volumes identified above are actual traffic volumes from traffic counts as opposed to simulated traffic volumes.
Simulated Travel Time (seconds) 85% of the travel time routes and segments, or a select number of critical routes and segments, as determined by the DTE or his/her designee, shall meet the calibration thresholds. Travel time routes should be determined in cooperation with the VDOT project manager based on project needs and goals.	Within ± 30% for average observed travel times on arterials Within ± 20% for average observed travel times on freeways The travel time should be calibrated for segments and routes separately or as deemed appropriate by the VDOT project manager.

Source: Adapted from VDOT, "Traffic Operations and Safety Analysis Manual (TOSAM) – Version 2.0," 31, Table 5, 2020 [71].

Figure 13.4 Maximum Desirable Error for Cutline/Screenline Volumes and Counts Errors



Source: CDM Smith, et al., "Analytical Travel Forecasting Approaches for Project-Level Planning and Design," 78, Figure 4-14, 2014 [66]; FHWA, "Calibration and Adjustment of System Planning Models,"1990.

Table 13.6 Highway Assignment Validation Procedures for Subarea and Corridor Studies

Type of Check	Subarea Study Types	
	Operation Analysis and Simulation for Small Areas (Using Windowing Method)	**Planning Studies for Large Area or Corridor (Using Focusing Method)**
R^2 between modeled volumes and counts on links	0.95	0.92
Percent root mean square error	See Table 13.7	See Table 13.7
Cordon line and screenline volume checks	< 54,000: ± 10 percent ≥ 54,000 and < 250,000: see Figure 10.2 ≥ 250,000: ± 5 percent	< 54,000: ± 10 percent ≥ 54,000 and < 250,000: see Figure 10.2 ≥ 250,000: ± 5 percent
Cutline volume checks	< 250,000: see Figure 10.2 ≥ 250,000: ± 5 percent	< 250,000: see Figure 10.2 ≥ 250,000: ± 5 percent
Speed checks	Use Table 13.5 as a reference to check speeds by segments and routes Conduct aggregate checks for congested and uncongested links separately and disaggregate checks of individual links Scatterplots of modeled versus observed speeds for peak and off-peak periods Speed versus V/C plots for peak and off-peak periods, by facility types.	Conduct aggregate checks for congested and uncongested links separately and disaggregate checks of individual links Scatterplots of modeled versus observed speeds for peak and off-peak periods Speed versus V/C plots for peak and off-peak periods, by facility types.

Table 13.7 Percent RMSE Guidelines for Subarea and Corridor Analyses

	%RMSE Guideline	
Volume Range	**Planning Studies for Large Area or Corridor (Using Focusing Method)**	**Operation Analysis and Simulation for Small Areas (Using Windowing Method)**
Less than 2,000	100%	90%
2,000 -4,999	65%	60%
5,000-9,999	45%	40%
10,000-14,999	35%	30%
15,000-19,999	30%	25%
20,000-29,999	27%	22%
30,000-49,999	25%	20%
50,000-59,999	20%	15%
60,000-69,999	18%	14%
>=70,000	15%	12%
Areawide (daily)	35%	30%

6. Forecasting and Model Output Refinements

To develop a future year subarea model, the enhancements in the validated base year model are generally carried over to the future to maintain the consistency, including the refined TAZ structure, network details, and others.

To serve the project level studies, model outputs are generally checked, refined, and adjusted, using the procedures which were originally established in NCHRP Report 255 and reiterated in NCHRP Report 765 [66]. Refining the model outputs is necessitated by the limitations inherent in a model, including the limitations in the model's spatial and temporal representation. The model outputs that are most often used to support project-level studies include volumes (link and turn) and speed (time). While the model validation is generally focused on link-level volumes and speed, turning movement volumes are seldom part of the validation.

Several different procedures are available to refine model outputs, as described in NCHRP Report 765 [66]:

- **Factoring procedures**, which use the relationship between the base and future model turning movements to grow the base year turning movement counts for the intersections under study:
  - The ratio method applies the ratio of the future year model turning movements to the base year model turning movements.

    - The difference method uses the difference between the future year model turning movements and the base year model turning movements.
    - Average of ratio and difference methods.
- **Iterative procedures**, which balance entering traffic and departing traffic volumes until an acceptable level of convergence is reached, using link volume forecasts and turning movement counts or estimate of turning movement percentages at an intersection.

When the windowing method is used, the future year O-D will need to be developed by adjusting the raw future O-D matrix from the model, based on the base year O-D estimation. The base year O-D matrix from the model is refined in the ODME process, and the differences between the refined O-D and raw O-D are computed and so are the ratios of the refined O-D to the raw O-D. Two approaches can be used to derive the refined future O-D—the "additive method," where differences are applied to the raw future O-D matrix, and the "multiplicative method," where the ratios are applied. The resulting refined future O-D matrix needs to be reviewed carefully, especially to identify those outliers that may result from large differences or ratios.

This process to derive the future O-D can also be carried out in another way, by using the refined base year O-D as the base and growing this base O-D to the future O-D based on the forecast growth between the base year model O-D and forecast year model O-D. The forecast growth can be applied to the base O-D through the "additive method," the "multiplicative method," or a combination of the two methods. This process is sometime called a "pivoting" process [72]. Some special cases need to receive extra attentions, including those cells with zero or with extreme growth. An extreme growth limit needs to be identified, and a threshold (X) is often determined to differentiate between normal and extreme growth, based on professional judgement. For a cell in the future O-D matrix, the estimation varies by combinations of special cases from the three matrix files – refined base year O-D (B), model base year O-D (Sb), and model future year O-D (Sf). Table 13.8 shows eight cases for a cell in these three matrix files and how/what a value for the future year will be estimated.

The refinement methods in Table 13.8 are also applicable to post-processing other model outputs, including link volumes and turning movements.

Table 13.8 Methods for Refining Model Forecasts for Future Year

Case	Refined Base Year (B)	Model Estimated Base Year (Sb)	Model Estimated Future Year (Sf)	Refined Future Year (P)
1	0	0	0	0
2	0	0	>0	Sf
3	0	>0	0	0
4	0	>0	>0 and growth<X	0
			>0 and growth>X	Sf-X
5	>0	0	0	B
6	>0	0	>0	B+Sf
7	>0	>0	0	0
8	>0	>0	>0 and growth<X	B * (Sf/Sb)
			>0 and growth>X	B * (X/Sb) + (Sf -X)

Source: Adapted from Daly, et al., "Pivoting in Travel Demand Models," 5, Table 1, 2012 [72].

Note. Refined base year matrix (B) from ODME, Model estimated base ear matrix (Sb) from a travel demand model. Model estimated future year matrix (Sf) from a travel demand model. X is a "threshold", which defines normal & extreme growth cases. X = 5*Sb, or five times the existing year output, is sometime recommended to differentiate between normal and extreme OD adjustment.

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