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A Report from the University of Vermont Transportation Research Center

Vermont Travel Model 2016-2017

Final Report

TRC Report 17-005
October 2017

James Sullivan and Karen Sentoff

Vermont Travel Model 2016-2017 Report

October 10, 2017

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Disclaimer

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1 Introduction

This report was prepared under the "Improvement and Operation of the Vermont Travel Model" contract with the Vermont Agency of Transportation (VTrans) for the 2016-2017 year (Year 9) of the contract. The primary objective of the project is to maintain and improve the Vermont Travel Model, ensuring that it remains a comprehensive, effective predictor of travel behavior of Vermonters. The purpose of this report is to document the activities which were completed in Year 9 of the contract to improve the functionality and currency of the Model. Other activities undertaken in Year 9 of the contract using the Model to support VTrans efforts, particularly analyzing the effects of construction traffic controls on regional flows, are documented separately.

The Vermont Travel Model is a series of computer sub-models which uses the land use and activity patterns within Vermont and its neighboring urban areas to estimate a typical day of travel behavior. Origin and destination matrices are created which describe the number of expected trips between geographical areas, known as traffic analysis zones (TAZs). Accommodations are made for commercial-truck trips and the occupancy characteristics of passenger vehicles. The final outputs are traffic volumes by roadway link in the state-wide roadway network. The Model currently includes 946 TAZs and 5,600 miles of highway-network links (Figure 1).

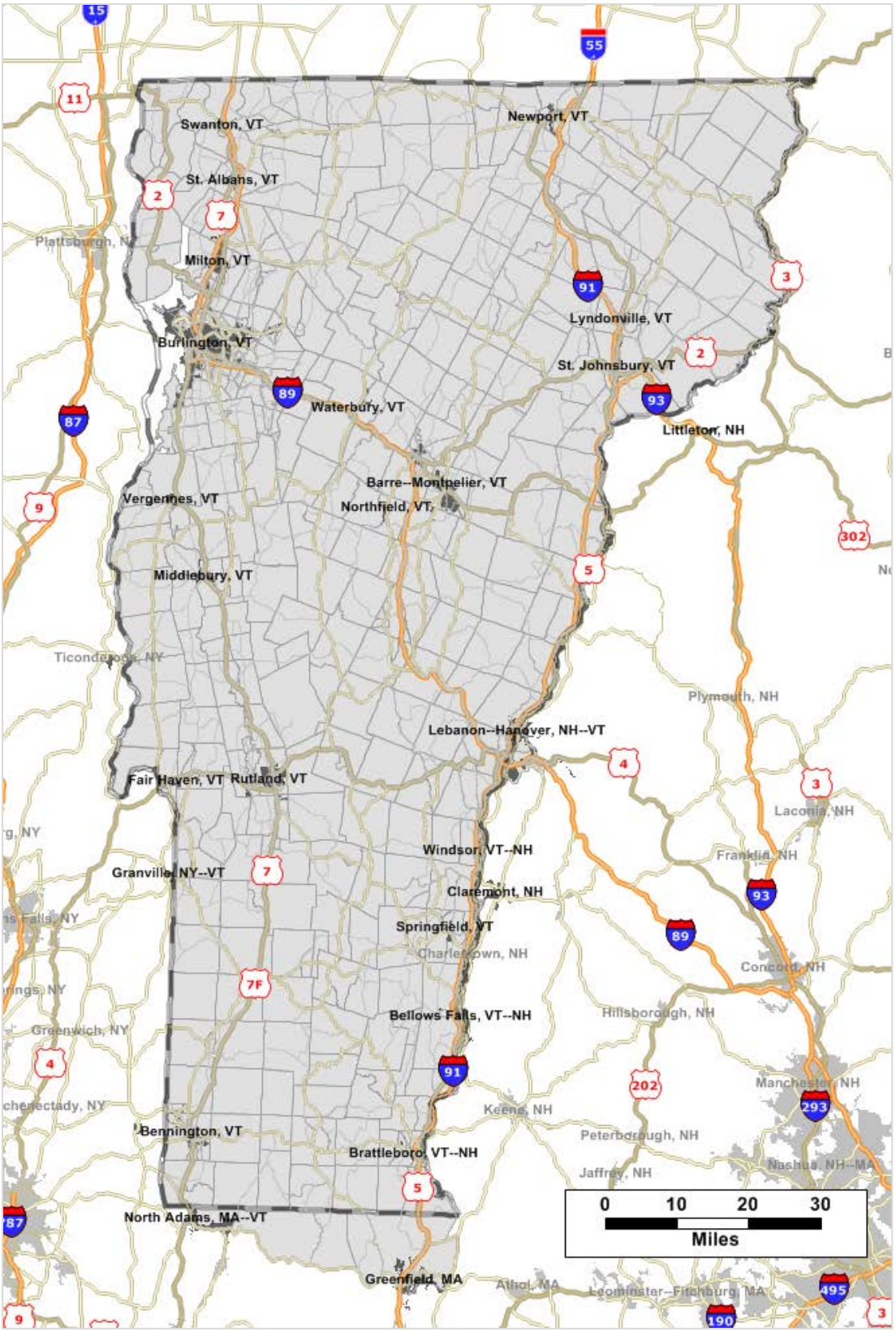


Figure 1 TAZs and Road Network in the Vermont Travel Model

2 Description of the Model

The purpose of the Vermont Travel Model ("the Model") is to estimate travel demand and link flow throughout the state using general spatial characteristics of the Vermont population. The Model is an important planning tool, beneficial not only to the Agency of Transportation but to regional planning commissions, the Chittenden County Metropolitan Planning Organization (CCMPO) and the University of Vermont Transportation Research Center (UVM TRC) – all of which rely on the Model for transportation planning and/or research. Daily travel demand is estimated by the Model between TAZs by trip purpose. From this travel demand, trips are routed and the flow of traffic on each link in the Model road network is estimated. Appendix A provides schematic representations of the Model inputs and processes, with written descriptions of its input data and its functions.

3 History of the Model and Summary of Previous Improvements

The original statewide model for Vermont was developed in the 1990s. At that time, the Model processes were run in the SAS Model Manager 2000 platform, and the network was in the TRANPLAN software format. The base-year 2000 version of the statewide model was updated beginning in 2003. The update was completed in 2007 with a transition to the GIS-based platform CUBE Voyager (VHB, 2007). During the 2003 – 2007 update, newly proposed or constructed links, like the Circumferential Highway in Chittenden County and the Bennington By-Pass, were added to the road network for accurate forecasting. Minor adjustments were also made to trip generation coefficients to bring initial balancing factors closer to 1.0. Other adjustments were made to improve the relationship between model outputs and validation data, which was down to 50.2% after the 2007 improvements (VHB, 2007).

In October of 2008, the Model was moved to the Transportation Research Center at the University of Vermont. For most of the 2008-2009 contract-year, the TRC conducted an evaluation of the Model's utility, components, and software platform. A report was completed in May of 2009 with details of the evaluation and its preliminary findings (Weeks, 2010). The UVM TRC also conducted a review of statewide travel-demand modeling practices in other states, including general model structures, and a discussion of emerging trends in travel-demand modeling (Weeks, 2010).

As the data from the National Household Travel Survey (NHTS) was released in the late summer of 2010, an update to the Vermont Travel Model was initiated by compiling auto-occupancies, trip rates, trip distributions, and trip-generation regression coefficients. This stage was completed by the end of Year 2. The Model update continued in Year 3 of the UVM TRC contract with new information from the 1,690 households in Vermont surveyed in the 2009 NHTS, new demographic information from the 2005-2009 ACS, new employment information for 2009 from the Vermont Department of Labor (VDOL), and new traffic counts for 2009 from VTrans.

In addition, sub-modules in the Model were re-evaluated and process improvements were made. Of the four data tables delivered with the NHTS (household, person, vehicle, and person-trip), only the household and the person-trip tables were used to update the Model. Using the household table from the NHTS, the trip-rates for all home-based trip productions were updated. With the person-trip table from the NHTS, the following were updated:

1. Trip-production and attraction regression equations in the Model
2. Vehicle occupancy rates by trip purpose
3. External trip-fractions by trip-purpose
4. Truck percentages by TAZ
5. Friction-factors in the trip-distribution module of the Model

The 2009 Average Annual Daily Traffic (AADT) for most of the major roads in the state was also used to make updates to the Model. This data was obtained in a GIS from VTrans and used to update the TRUCK purpose O-D using an origin-destination matrix estimation (ODME) process on the AADTs for truck and the daily trip counts for all external TAZs in the Model.

Finally, land-use characteristics in the Model were also updated using the 2005-2009 ACS (for numbers of households) and the employment statistics from the VDOL (for numbers of jobs by category).

The importance of these updates was immediately apparent in the fidelity of the Model. For example, the base-year 2000 Model included 240,637 households in its 628 TAZs, with an expected growth to 295,126 households by 2020. The 2009 update showed that there would be closer to 250,000 households in Vermont at that time, indicating that the expected growth had been grossly overestimated. Employment growth, however, was underestimated in 2000. The total employment of 333,409 in 2000 was expected to grow to 428,353 by 2020. However, the 2009 update revealed a total of 431,280 jobs in Vermont, already surpassing the 2020 estimate. Part of this discrepancy could be due to improved job totals from the VDOL which may not have been readily available in 2000.

The Model updates completed in Year 4 brought its base-year up to 2009-2010. Land-use characteristics were updated in Year 4 with new information from the 2006-2010 ACS, the 2010 US Census, and the 2009 employment estimates from the Bureau of Economic Analysis (BEA). The improvements created by these updates were evaluated by checking the Model outputs for "reasonableness" in accordance with FHWA guidance (FHWA, 2010). FHWA standards for comparing Model flows with traffic counts were achieved for 3 of the 4 roadway classes tested. The only exceedance of the FHWA standards was for freeways. Most of the freeways in the Model are coded as two separate links, one for each direction of travel, to accommodate coding of ramps at freeway interchanges. However, the AADT data used to validate the Model is coded as single-links throughout the state, even for freeways. This discrepancy creates a susceptibility for the traffic counts to be mistakenly applied when the coding of the links is not taken into account.

The Model improvements conducted in Year 5 included Model-process improvements, significant improvements to the network representation of the state-maintained roadways in the Model, and forecast-year Model runs for 2025 and 2035. Each of these improvements took advantage of data available in other Sections at VTrans, and much of the data had to be pre-processed for use in the Model's GIS environment. These improvements resulted in an overall improvement in the ability of the Model to simulate a typical day of travel in the state. The forecast-year Model runs were conducted with realistic representations of the state-maintained roadway network in 2025 and 2035, based on long-term transportation plans prepared by VTrans and the RPCs.

A TMIP peer review of the Model was conducted by FHWA in Year 5, resulting in a comprehensive set of recommendations for Model improvements for Year 6 and beyond. Selected subtasks were recommended based on the short-term recommendations from the peer review to achieve this goal:

1. Break up HBO and NHB trips in the Model with sub-categories (personal-discretionary, personal non-discretionary, and business) and/or distance classes (long and short) as data supports
2. Test the validity of leaving the trip matrices asymmetrical, particularly for NHB travel, since NHB trips do not necessarily return to their origin daily
3. Re-assess all centroid connectors locations and resolution of TAZs
4. Explore the need for seasonal trip tables
5. Develop a Validation Plan for the Model, along with a user's guide and technical reference
6. Expand the spatial boundary of the Model as necessary to include important "halo" populations
7. Develop a statewide model users' guide and technical reference
8. Consider dynamic traffic assignment to assess traffic patterns in emergency response
9. Identify metrics for emergency scenario comparison to guide model development

Through Year 9, all of these improvements have been completed, with the exception of #4 and #9.

The Model improvements conducted in Year 6 included Model-process improvements and improvements to the network representation of the state-maintained roadways in the Model. The Agency decided to change the software platform for the Model in Year 6, from CUBE Voyager to TransCAD. This decision was based on the following points:

1. The Chittenden County Regional Travel Demand Model is in TransCAD, so this change would facilitate synchronization of the two models
2. The UVM TRC, which hosts the Model, has developed other transportation and land-use models, like the roadway snow and ice control routing model and the Network Robustness Index calculator, for Vermont, in TransCAD, so this change would facilitate potential integrations of those models and the Vermont Travel Model

In addition to migrating the code, other refinements were made to the Model code in TransCAD, and new features were added. The most significant refinement was a change to the way that truck trips are estimated in the Model. Since TransCAD has a macro for utilizing an ODME procedure, that procedure was incorporated into the Model code. The original procedure was less accurate, because it used truck traffic counts but in a more aggregate way, and then applied those counts to the overall trip counts to extract an estimate of truck trips by TAZ. With the ODME procedure, truck traffic counts are used directly to estimate truck trips for the entire state at once, based on an initial "seed" matrix. This refinement improved both the speed and the accuracy of the Model.

New features added to the Model included a menu-based user-interface with full specification of the input files, a forecast-period specification, and the addition of a root-mean-square percent error (RMSPE) output table. A new menu-interface was added to help the user explicitly understand how the Model is run, and to allow the user more explicit control over the Model runs. The forecast-period specification allows the Model to be run to any forecast year the user chooses, creating a sub-folder in the output folder identified by the forecast year with the associated Model outputs. A new output table was added to the Model to help users see the RMSPE and link-specific squared errors (SE) more efficiently. These statistics are useful for validating the Model, so having them produced in a stand-alone output table allows the Model to be re-estimated and/or calibrated more efficiently.

Following the recommendation of the peer-review panel from Year 5, a comprehensive analysis of long-distance travel in Vermont was conducted, with the goal of creating a new classification of trips in the Model based on distance. A new distance-classification was explored with a cut-off distance of about 40 miles, with trips longer than 40 miles considered "long-distance"

trips. However, existing data resources, like NCHRP 735, for creating a long-distance trip sub-model were found to be inaccurate for Vermont and inadequate for a complete specification of long-distance travel. Model improvements conducted in Year 7 included significant improvements to the way trips are distributed to destinations, with the addition of new distance classifications for all non-TRUCK trip purposes. New rates and parameters which include the long-distance classification (and a "short-distance classification") were incorporated into the Model platform in Year 7.

Continuing improvements to the network representation of the Model road network included adjustments to the locations of centroid connectors in the vicinity of the University of Vermont, one of the largest employers in the state. A few other links with no flow were found to have incorrect speed limits, leading to unusually high assumed travel times across them. Speed limits were checked and fixed using a Google Street View Hyper-Lapse and the results improved significantly. The TAZ resolution was assessed by focusing on those TAZs in the network with the highest total trip counts as an origin or a destination. The top 5 TAZs for trip counts were found and two of them were split to create a new TAZ at each location. These splits were necessary because of significant development that has occurred in previously rural locations at the edges of the cities of St. Albans and Barre. These improvements resulted in an overall improvement in the ability of the Model to simulate a typical day of travel in the state. The overall RMSPE of the Model was at 42.5% after the Year 7 improvements.

The Model improvements conducted in Year 8 included the development and implementation of a new truck sub-module for truck trip generation, the calibration and validation of the Model with its new expanded boundary, and the completion of the initial analysis of external regions to support development of an external-travel sub-module in Year 9.

4 Description of the Data Used in 2016-2017

This section contains a description of the data sources used in the Model improvement activities for Year 9.

4.1 The 2011 – 2015 American Community Survey

Demographic data from the American Community Survey (ACS) 5-year estimates for the period from 2011 to 2015 (USCB, 2017b) were used to update 2015 household characteristics for the 2015 update/calibration. The American Community Survey (ACS) is an ongoing survey by the U.S. Census Bureau that began in 2005 and provides data every year. The intention is to give communities the current information they need to plan investments and services. The ACS is conducted every year to provide up-to-date information about the social and economic needs of American communities between the decennial censuses. However, the geographic representation of a single-year ACS for a rural state like Vermont will typically be very poor. However, ACS pooled-data can be used to obtain improved demographic, social, economic, and housing characteristics data. Since 2005, ACS data has been pooled over multiple years to produce stronger estimates for areas with smaller populations. Data are combined to produce 12 months, 36 months or 60 months of data. These are called 1-year, 3-year and 5-year data. Although single-year ACS estimates are typically only valid for areas with populations over 65,000, the pooled 5-year data is valid for populations of almost any size.

4.2 2015 Employment Data

New Hampshire and Massachusetts track employment similarly to Vermont. Town-by-town data are available online for New Hampshire through its Economic and Labor Market Information Bureau of the New Hampshire Employment Security Division at http://www.nhes.nh.gov/elmi/statistics/qcew-data.htm. Covered employment & wage data by industry for workers covered by unemployment insurance was obtained for Lebanon and Hanover for 2010. This data is based on Quarterly Census of Employment and Wages (QCEW) program files extracted from quarterly tax and wage reports submitted by employers in the town. Massachusetts makes its employment and wage data available through the website of the Executive Office of Labor and Workforce Development

(EOLWD) at http://lmi2.detma.org/lmi/lmi_es_a.asp. These data are derived from reports filed by employers subject to unemployment compensation laws, both state and federal. Industry employment and payroll information is produced both quarterly and annually and aggregated for the cities and towns by NAICS code.

The BEA regional economic accounts provide statistics about employment for states and counties, as well as personal income for states, counties, metropolitan areas, micropolitan areas, metropolitan divisions and combined statistical areas, and BEA economic areas. BEA prepares estimates for 3,111 counties, 363 metropolitan statistical areas, 576 micropolitan statistical areas, 123 combined statistical areas, 29 metropolitan divisions, and 179 BEA economic areas. The estimates of compensation and earnings by place-of-work indicate the economic activity of business and government within an area and the estimates of personal income by place of residence provide a measure of fiscal capacity of an area. The county employment estimates are a complement to the place-of-work earnings estimates. The employment estimates are designed to conform conceptually and statistically with the place-of-work earnings estimates; the same source data—generally from administrative records—are used for both the earnings and employment estimates whenever possible. The earnings estimates reflect the scale and industrial structure of an area's economy rather than the income of the area's residents. Therefore, the employment estimates measure the number of jobs in a county, instead of the number of workers who perform the jobs. The characteristics of the county employment estimates follow from this concept and from the characteristics and limitations of the available source data. For Year 9, the BEA estimate of total full-time and part-time employment by NAICS industry by County for 2015 was used.

4.3 2015 Annualized Average Daily Traffic

Traffic counts were needed to calibrate the 2015 soft update for Vermont, New Hampshire and Massachusetts. A GIS with AADTs for 2015 was obtained for Vermont and values in the GIS that corresponded to links in the Model road network were imported so that they would be included in the calculation of the 2015 RMSPE. For Massachusetts, the updated statewide road inventory GIS with AADTs for 2015 was obtained from the Massachusetts DOT at http://geo-massdot.opendata.arcgis.com/. For New Hampshire, since the set of roads in Lebanon and Hanover for which 2015 AADTs are needed is relatively small, the appropriate values were translated directly from the traffic volume reports at https://www.nh.gov/dot/org/operations/traffic/tvr/locations/index.htm.

4.4 TransCAD Streets Network

The streets network that is included with the TransCAD software includes all public streets and highways in North America. Each link is identified with a unique ID, and the following characteristics:

- Length
- Direction of Travel
- Name
- Alternate Name
- Class
- Type
- Divided

The streets network was used to extend the Model road network throughout New England, New York state, and Quebec in support of the external travel sub-module.

5 Improvements Methodology and Results

Model improvements undertaken in Year 9 were in accordance with the recommendations provided by the peer review panel during the TMIP Peer Review during Year 5 and standard best practices for Model improvement. The following improvements were completed:

1. External trip distribution sub-model
2. 2015 soft update and calibration

5.1 External Trip Distribution Sub-Model

Building on the work completed in Year 8, the research team was tasked with developing the external distribution sub-model, for estimating and distributing trips between Vermont and the rest of the northeastern U.S. and Quebec – places likely reachable by highway in a day or less. Vermont's "highway-shed", shown shaded in Figure 2, includes places outside the Model boundary external trips are likely destined for.

Figure 2 Vermont's "Highway-Shed"

UAs within 100 miles of the Vermont border and UCs within 50 miles of the Vermont border in the northeast U.S. were included as part of the Vermont "highway-shed", as well as Census metropolitan areas (CMAs) and Census agglomerations (CAs) within 100 miles of the Vermont border in Canada.

Each of these external places was made into an external TAZ in the Model. First, the Model road network was expanded to encompass all of these external places throughout New York state, all of the New England states, and Quebec. Outside of Vermont, only interstates, federal highways, and state highways are included. This step was accomplished by importing the TransCAD network of major highways in the region outside of Vermont, then merging it with the internal Model network. Next, speed limits were estimated for each major highway outside of Vermont according to the highway's functional class, whether it is in an urban or rural area, whether it is divided, and the number of lanes of travel in each direction, all of which were available from the TransCAD source layer.

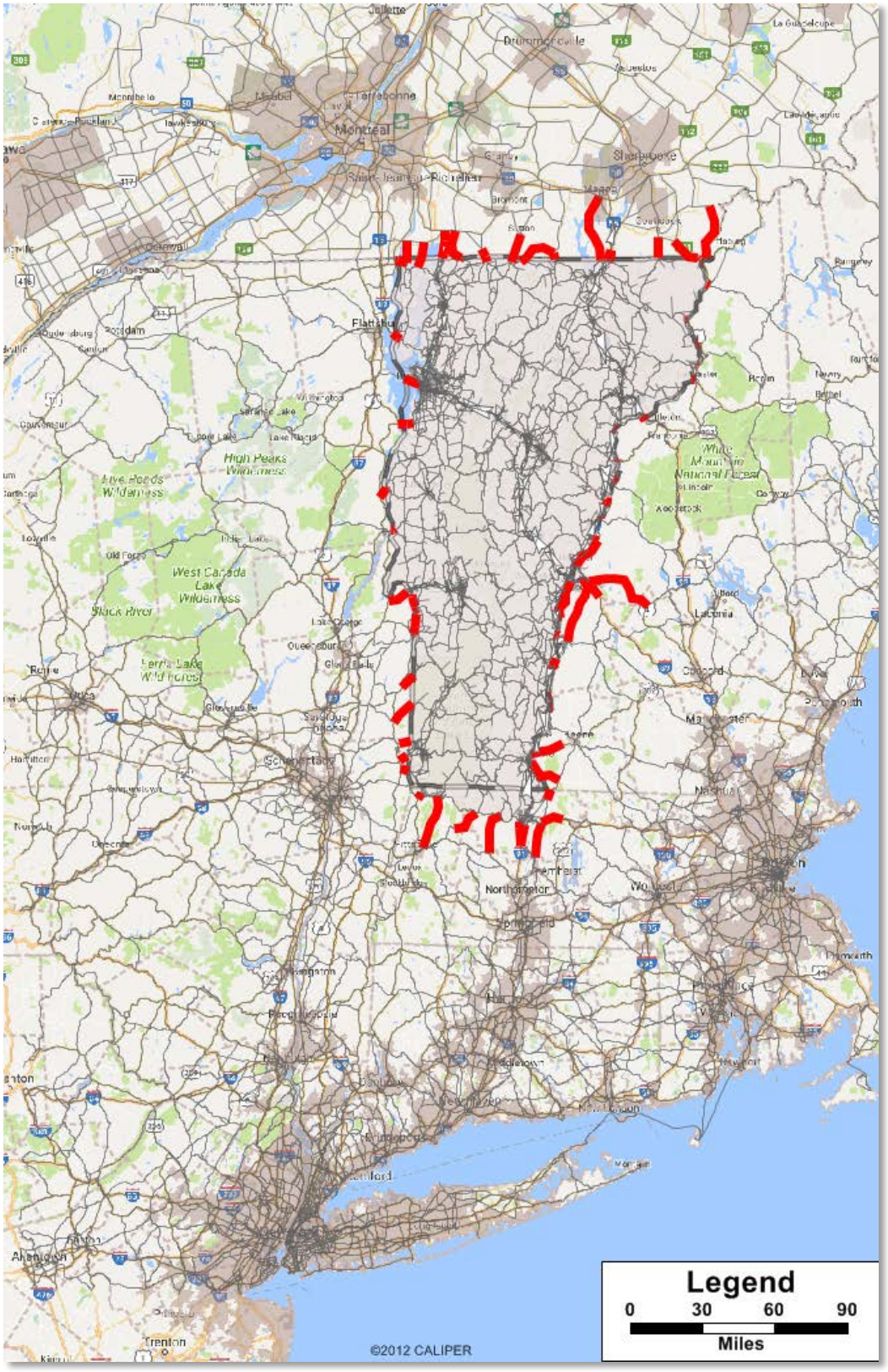
Next, the external UAs, UCs, CMAs, and CAs were exported from the geographic files containing them, and then merged with the existing TAZ layer. Then, each node in the expanded Model road network closest to the centroid of each external TAZ was identified and flagged as a new centroid in the road network.

Estimating the number of trips from each external TAZ and Vermont was accomplished by distributing the counts from the Vermont border according to selected characteristics of the TAZ and its distance from the Vermont border. The estimation process included 4 distinct steps:

1. Constraining trips to external TAZs with external connector traffic
2. Constraining the distribution of external-external trips
3. Calibration of the new external sub-module
4. Constraining trip purposes for E-I and I-E trips

5.1.1 Constraining trips to external TAZs with external connector traffic

The first step in distributing trips to Vermont from each of these 84 external TAZs was to restrict the number of trips likely to cross the Vermont Model boundary at one of its 63 "external connectors" shown in Figure 3.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Ogdensburg
Potsdam
Canton
Watertown
Old Forge
Utica
Rome
Hamilton
Norwich
Oneonta
Binghamton
Trenton
Kingston
Ellenville
Middletown
Poughkeepsie
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Laconia
Berlin
Gorham
Conway
Portsmouth
Dover
Rochester
Plymouth
Bethel
Rumney
Newry
Fryeburg
Lewiston
Auburn
Augusta
Waterville
Skowhegan
Bangor
Brewer
Old Town
Orono
Millinocket
Presque Isle
Caribou
Edmundston
Woodstock
Fredericton
Saint John
Moncton
Dieppe
Riverview
Sackville
Amherst
Truro
Halifax
Dartmouth
Bedford
Sydney
Glace Bay
New Glasgow
Antigonish
Charlottetown
Summerside
Moncton
Saint John
Fredericton
Woodstock
Edmundston
Campbellton
Bathurst
Miramichi
Chatham
Newcastle
Dieppe
Moncton

External connectors are links in the road network that cross the boundary between internal and external TAZs. Each external connector was paired with a set of external TAZs that travelers using the connector on a typical day might be destined for.

For example, the connector representing I-89 where it leaves the Model boundary in Lebanon—Hanover, NH might be used for travel between Vermont and any of the following destinations in the Vermont highway-shed:

- Concord, NH
- Hillsborough, NH
- Peterborough, NH
- Boston, MA--NH--RI
- Dover--Rochester, NH--ME
- Lewiston, ME
- Manchester, NH
- Nashua, NH--MA
- New Bedford, MA
- Portland, ME
- Portsmouth, NH--ME
- Worcester, MA--CT
- Providence, RI--MA

Developing this subset is possible because it is very unlikely that any travel to or from Vermont would use this external connector to reach, for example, New York City or other external TAZs to the south and west of Vermont. In this way, the set of external TAZs for this external connector are paired with the AADT of the connector – 19,600 vehicles per day, limiting the estimated sum of the trips to and from its set of destinations and Vermont. These relationships were expanded to "many-to-many" pairings, with multiple external TAZs expected to use an external connector, but each destination also expected to use multiple connectors.

5.1.2 Constraining the distribution of external-external trips

Travel between external TAZs must be constrained in a state travel model. If the Model is only concerned with travelers that enter, leave or pass through the state, trips between external TAZs that do not pass through the state must be excluded. Due to Vermont's geographical position in the northeastern U.S., predicting which external-external (E-E) trips would not

be likely to pass through Vermont is relatively straightforward. First, the external TAZs are grouped into regions relative to the locations of major external connectors that would facilitate through-state trips:

- Group A: External TAZs in New York State from Albany clockwise to the Canadian border
- Group B: External TAZs from the I-91 corridor in Connecticut and Massachusetts counterclockwise up through Rhode Island, New Hampshire, and Maine to the Canadian border
- Group C: External TAZs in Canada
- Group D: External TAZs from the I-89 corridor in New Hampshire counterclockwise up through the rest of New Hampshire to the Canadian border (a subset of Group B)
- Group E: External TAZs representing New York City and surrounding UAs

Each of the regions represented by these groups are shown on Figure 4.

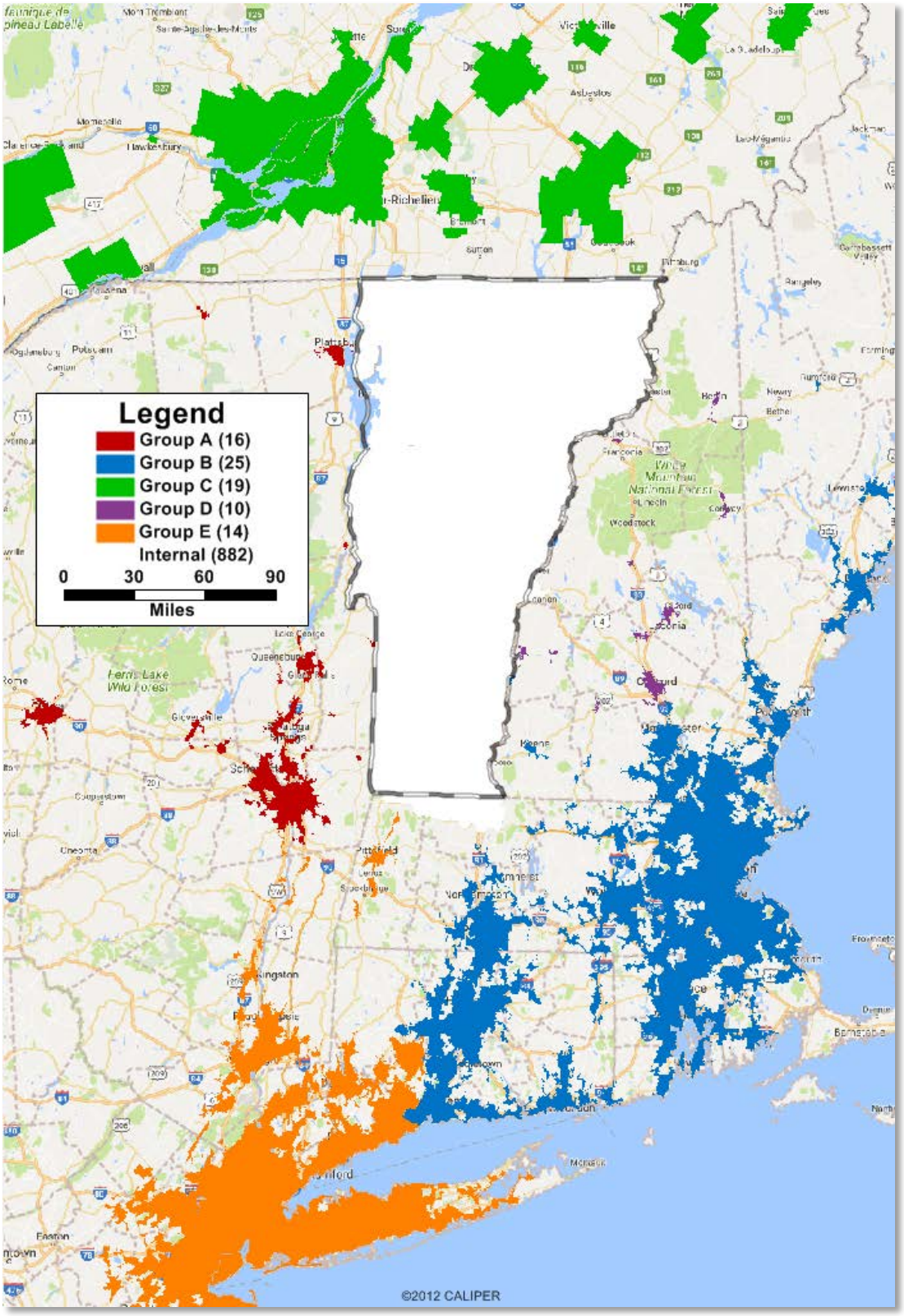

Figure 4 Regional Groupings of External TAZs in the Vermont Travel Model

Using these groupings, the following pairs of groups were identified as likely to pass through Vermont:

- Group A to/from Group D
- Group B to/from Group C

All other pairs, and all intrazonal trips, are not likely to pass through Vermont and are excluded. These exclusions are represented in the trip matrix in Figure 5. The Model code was adjusted at the trip distribution step to prohibit the distribution of E-E trips where excluded. Additional details on the trip distribution step can be found in Appendix A.

Group	A	B	C	D	E
A	No	No	No	Yes	No
B	No	No	Yes	No	No
C	No	Yes	No	No	No
D	Yes	No	No	No	No
E	No	No	No	No	No

Figure 5 Exclusions and Permissions for E-E Trip Distribution

5.1.3 Calibration of the new external sub-module

Determination of significant characteristics and initial external trip estimates. A series of step-wise, reductive regressions were undertaken to identify the characteristic(s) of the external TAZs that are most related to the estimated number of Vermont trips. The regression was undertaken using the external connector AADTs as the independent variable, and the aggregated characteristics of the TAZs it is paired with as the dependent variables. Table 1 lists the characteristics of the external TAZs in the U.S. that were found to be the most effective predictors of the AADTs at the Vermont border, along with the results of the regression.

Table 1 TAZ Characteristics for Predicting Vermont Trips

Field Name	Estimate	Std. Error	T Test
% of households with no vehicle available	-103,914	50,280	-2.07
Median age of workers	-1,298	633	-2.05
No. of passenger vehicles available	0.015	0.004	3.72

UAs and UCs with more "no-vehicle" households had fewer Vermont trips, attesting to the need for an available vehicle to take long-distance highway trips, and possibly pointing to the tendency for higher-income households to have the opportunity to take these types of trips. A lower median age of workers also corresponded to more Vermont trips, as did the total availability of passenger vehicles. Availability of passenger vehicles is an important variable when trips to/from the largest UAs in the Model are considered. Although the New York City UA is much larger in overall population than the Boston UA, the number of passenger vehicles available in each is not as different (4.4 million and 1.5 million, respectively). As shown in the table, the number of passenger vehicles was the strongest contributor to the regression model, and the only characteristic positively associated with Vermont trips. Therefore, a final reductive step was taken to eliminate the other two characteristics from the regression, leaving only the number of passenger vehicles available in the UA or UC as the most effective predictor of Vermont trips.

The data set for Canadian CAs and CMAs was more sparse, with only 19 total areas and a maximum external-connector 2015 AADT of only 3,300. Therefore, a more direct approach was taken to identifying significant correlations, by analyzing a correlation matrix of all CMA and CA characteristics and AADTs at the Vermont external connectors. The strongest correlation coefficients with AADTs existed for:

- Median employment income (0.6), and
- Median commuting duration (0.4)

Other characteristics with correlation coefficients of 0.4 were cross-correlated to one or both of these characteristics, so they were not kept in the final predictive model. Therefore, these two characteristics were assumed to be the best predictors of trips between Vermont and the set of 19 Canadian CAs and CMAs.

Gravity Model application to external TAZs. From these of attributes, a Gravity Model was used to distribute trips between Vermont and the external TAZs. Trips represented by the AADTs were distributed from external connectors to/from each of the external TAZs that were constrained to use that connector. The distribution of trips for each external TAZ was determined by its share of the total characteristic amongst all other external TAZs constrained to use that connector, and by a friction factor calculated from its distance from the Vermont border. Distance from the Vermont border *(d)* was used to create a friction factor *(ff)* for each external TAZ *i* using an exponential functional form:

$$ff_i = \frac{1}{e^{q \cdot d_i}}$$

In the formula, q is a "decay coefficient" that can be adjusted based on the effect of travel time in predicting the attractiveness of trips to/from Vermont. Using this formula, though, external TAZs that are very close to the Vermont border create unrealistically high friction factors. Therefore, the equation was modified to include a "cut-off" value, beneath which the actual distance of the external TAZ from the Vermont border was not used, but a proxy distance at the "cut-off" value was used instead:

$$d_i = x \; for \; all \; d_i < x$$

This assumption creates a set of friction factors with a plateau at values of d lower than x, as shown in Figure 6 for x = 40.

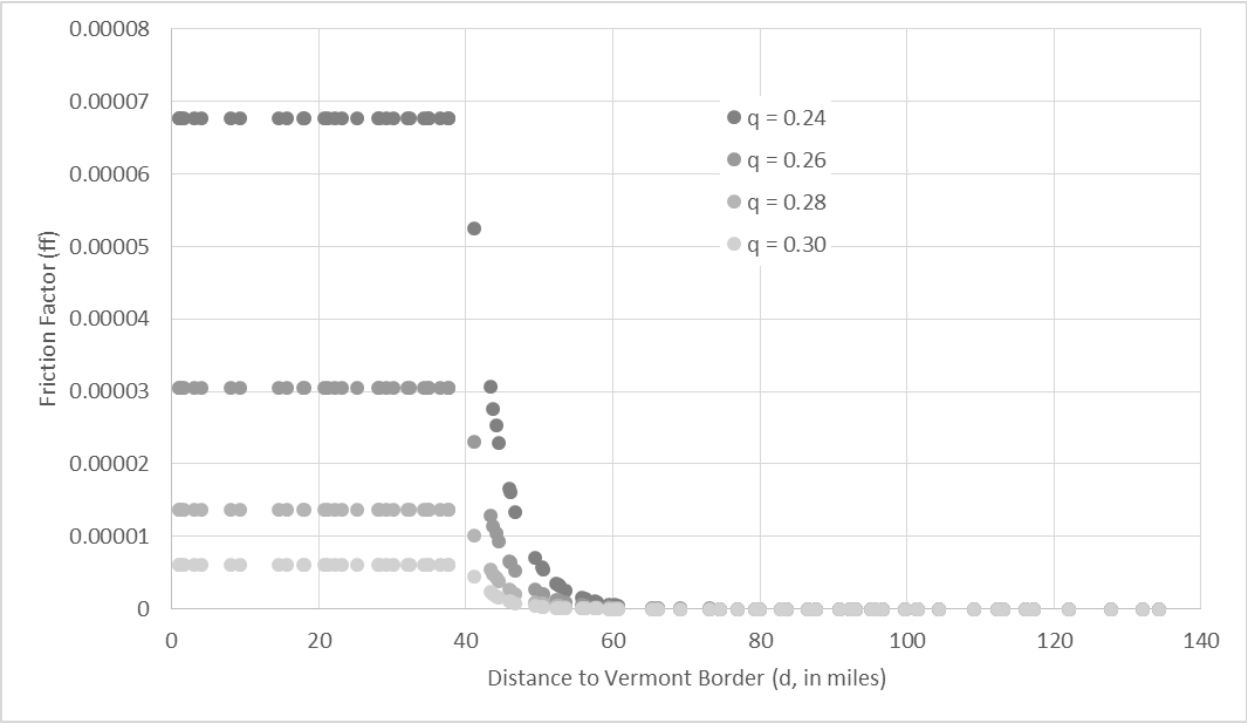

Figure 6 Friction factor distributions for exponential function with a "cut-off" of 40 miles

Adjusting the decay coefficient (q) and the cut-off (x), a series of external distributions were found by applying the Gravity Model form:

$$T_{ic} = AADT_C \frac{\frac{p_i}{P_c}\frac{ff_i}{FF_c}}{\sum_C \frac{p_i}{P_c}\frac{ff_i}{FF_c}}$$

In this form, p_i represents the relevant characteristic of TAZ i (number of passenger vehicles available for U.S. TAZs or a sum of the normalized median employment income and median commuting duration for Canadian TAZs) and P_c represents the sum of those characteristics for all TAZs constrained to external connector c. T_{ic} is the total number of trips between TAZ i and Vermont using external connector c, assumed to be a fraction of the total AADT on external connector c ($AADT_c$). To find the total number of trips between TAZ i and Vermont (T_i), these values are summed for all external connectors that are used by these travelers:

$$T_i = \sum_C T_{ic}$$

This Gravity Model application allowed the determination of a series of external trip distributions corresponding to a variety of decay coefficients and cut-off values.

A supplemental component was added to the application to "cap" the number of possible trips between the U.S. TAZs and Vermont at the number of passenger vehicles available in it. This supplemental step was especially important for small, nearby external TAZs in the U.S., which often received a total number of trips that exceeded the number of passenger vehicles available – a very unrealistic situation. After capping the trips to/from Vermont at the number of passenger vehicles in the UA or UC, the trip distribution was programmed to redistribute the trips exceeding the caps to other external TAZs according to their share of passenger vehicles amongst the external TAZs that had not yet been exceeded.

Each time the Gravity Model was applied, the results of the Model run were assessed using the RMSPE of the fit between the AADTs and the daily flows for the base year (2010). Table 2 provides the results of this assessment for a variety of values of q and x.

Table 2 Results of the calibration of q and x

Friction Factor Decay Coefficient, q	Cut-off, x (mi.)	RMSPE
0.24	0	49.2%
0.26	0	47.7%
0.28	0	47.5%
0.30	0	47.3%

Friction Factor Decay Coefficient, q	Cut-off, x (mi.)	RMSPE
0.28	10	46.3%
0.30	10	46.5%
0.28	20	46.6%
0.30	20	**45.6%**
0.28	30	47.7%
0.30	30	46.2%

These results indicate an optimal decay coefficient of 0.30 and an optimal cut-off distance of 20 miles. This calibration resulted in the distribution of Vermont trips shown in Figure 7.

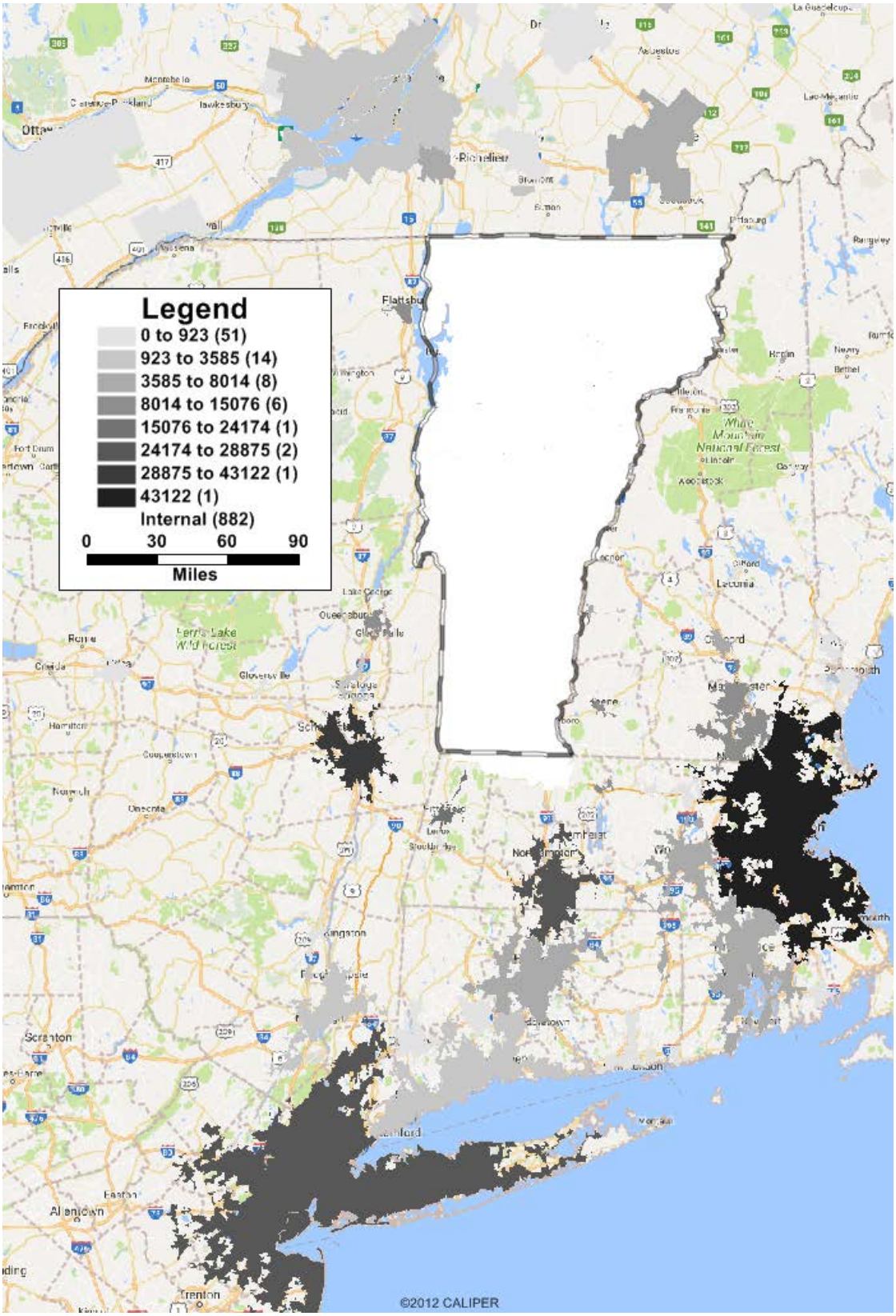

Figure 7 Calibrated external distribution of Vermont trips

The external TAZ representing the Boston urban area generates the largest number of Vermont trips, due to its proximity to Vermont and its high number of available passenger vehicles (1,504,405). This TAZ is followed by those representing Albany-Schenectady, New York-Newark, and Springfield (MA).

A variety of other sensitivity tests were run, using the RMSPE to re-calibrate some of the Model functions that, until now, had been assumed. First, a variety of traffic assignment types were tested – the current traditional user-equilibrium (UE) approach, the all-or-nothing (AON) approach, and a stochastic user-equilibrium (SUE) approach. The SUE approach for traffic assignment performed best, with a RMSPE of 45.7, whereas the UE resulted in a 46.6% and the AON resulted in a 50.5%. Therefore, the Model code was adjusted to incorporate an SUE approach.

Next, a variety of assumptions for free-flow traffic speeds were tested. Free-flow speeds that are 5, 10, and 15 mph above the speed limit were all tested, as well as an assumption that all free-flow speeds are 20% higher than the speed limit. The results indicated that the current assumption, of free-flow speeds 10 mph above the speed limit, was the most accurate. Therefore, the Model code was left unchanged for the estimation of free-flow speeds.

Finally, a variety of daily roadway capacities were tested, as an adjustment to the theoretical capacities calculated in Year 4 (Sullivan and Conger, 2012) from the methods in the Highway Capacity Manual. Daily capacities 10% higher, and 10, 15, 20, 25, and 30% lower than the calculated capacities were tested. It was found that a 15% reduction from the theoretical value resulted in the best RMSPE. This finding makes sense because often roadways exhibit deterioration that reduces their effective capacity, and 15% is a reasonable expectation for pavements exposed to the type of weathering that is experienced in Vermont. Therefore, the daily capacities used by the Model in the traffic assignment step were assumed to be 15% lower than the theoretical capacities for each link.

5.1.4 Constraining trip purposes for E-I and I-E trips

External trips in the Model include those that begin or end in Vermont (E-I / I-E) and those that pass through it but begin and end outside of Vermont. For E-I / I-E trips, the distance from the Vermont border to the external TAZ that they reach creates a distinction – between trips that are more common and routine in nature and those that are less frequent, associated with traditional long-distance and overnight travel. Since the 2009 NHTS, upon which the Model's trip-making behaviors are based, includes only routine travel by Vermonters and undercounts infrequent long-distance trips, the trip-purpose breakdown determined from it should only apply to the more

common trips. Long-distance and overnight travel would fall entirely in the non-home-based – long-distance (NHB-LD) purpose category.

To distinguish these two types of E-I / I-E trips, zones that are within a "buffer distance" of the internal boundary of the Model were assumed to be in the "routine" purpose-group. This group generally included UAs and UCs in northern New York State, western Massachusetts (from I-91 west), and northern New Hampshire, along with Montreal, Granby, and Sherbrooke in Canada. Other external TAZs were assumed to be in the "long-distance" purpose-group, with all Vermont trips in the NHB-LD category. Figure 8 shows the sets of external TAZs in each purpose-group assuming a buffer-distance of 60 miles, along with the area covered by internal TAZs.

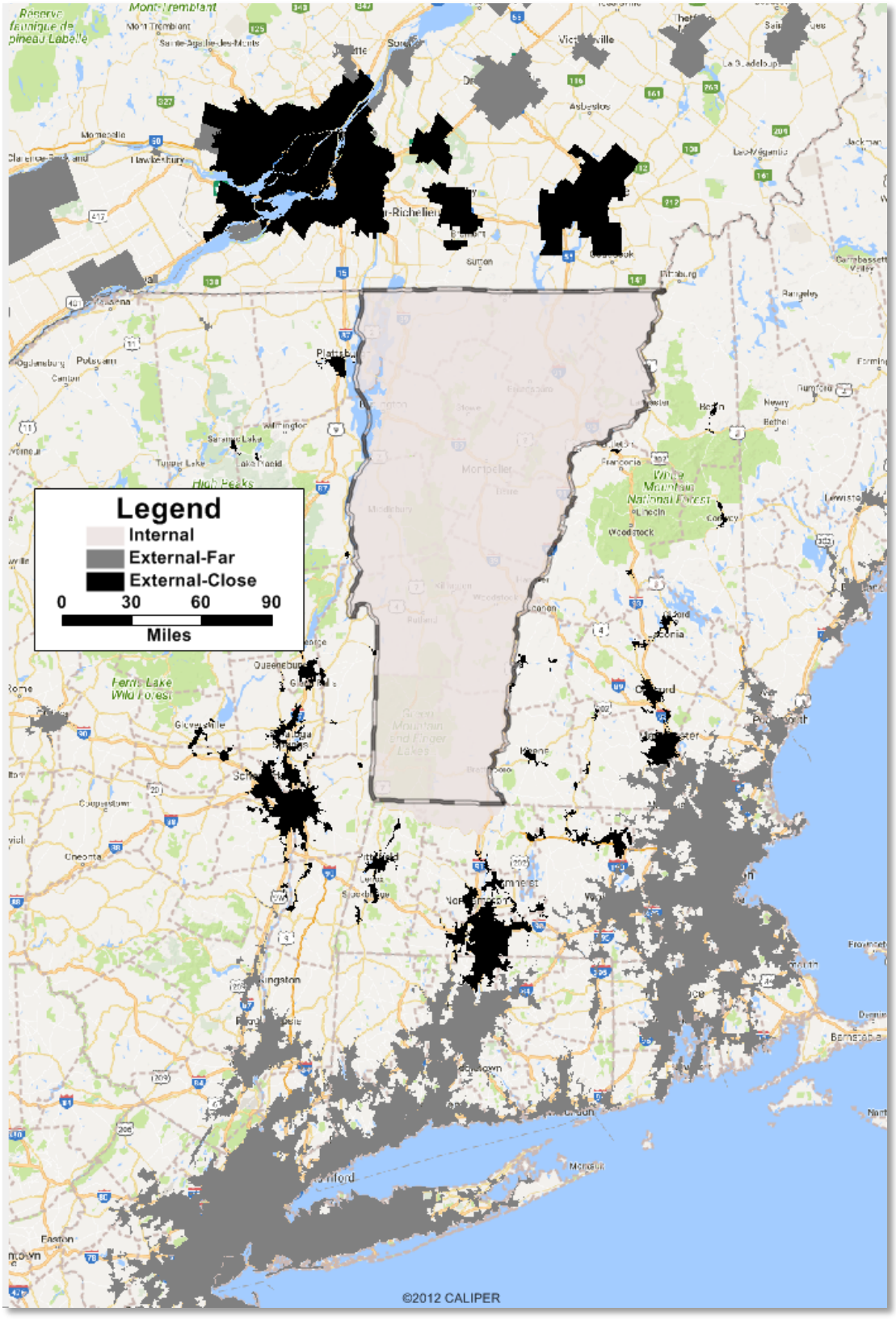

Figure 8 Example of Purpose-Groups for External TAZs at a Buffer Distance of 60 miles

In order to understand the optimal buffer-distance where the distinction between E-I and I-E trip purposes would be effective, the Model was run for a variety of buffer distances and the RMSPEs were calculated. The results are shown in Table 3.

The results show that the reduction of purposes to NHB-LD beyond a buffer distance from the Model boundary should be eliminated, with all E-I and I-E trips assumed to have a full range of purposes consistent with what was revealed in the NHTS for Vermonters.

Table 3 Results of the calibration of the buffer distance for purpose-groups

Buffer distance (miles)	2010 RMSPE
20	55.0%
30	50.7%
40	49.6%
50	46.7%
60	46.1%
70	45.2%
90	44.1%
Unlimited	**43.7%**

5.2 2015 Soft Update and Calibration

Once the external sub-module had been calibrated, a soft update was conducted by calibrating the Model's growth forecasting ability to empirical 2015 data. First, AADTs were gathered for the 2015 update year and incorporated into the Model road network. Next, an automatic 5-year forecast was incorporated into the Model code, with the outputs sent to a new "2015 Update Year" folder, reserving the "Forecast Year" output folder the outputs of the actual forecast (which now has to be greater than 5 years). In addition, an extra step is added to the Model code to calculate a RMSPE between the 2015 Model flows and the 2015 AADTs. The result of this unadjusted Model for the 2015 RMSPE was 46.0% (with the base-year RMSPE still at 43.7%). This value provides a starting point for the 2015 update and calibration.

Areas of significant disagreement between the Model flows and the 2015 AADTs represent regions that are not well represented by the Model. These areas include external connectors for I-91 in Greenfield and I-89 in Lebanon-Hanover. Both of these areas are newly added to the Model, and lack specific spatial resolution. In the future, the resolution of TAZs and roadways in the Model in these areas can be improved and should lead to a closer match with 2015 AADTs. In addition, these links represent the largest external

connectors in the Model, linking Vermont to the metropolitan areas to the south (Boston and New York). The Model's trip generation sub-module for these external TAZs is still in its infancy, so its accuracy will improve greatly over time.

Next, new land-use characteristics (household counts, household structures, and employment totals by job type) were gathered for 2015 for all of the internal TAZs in the Model, including all of Vermont, and towns in New Hampshire (Lebanon and Hanover), and Massachusetts (9 other towns in Berkshire and Franklin counties). The same data sources were used for the 2015 update year as had been used for the 2010 base year – household counts and structure came from the U.S. Census' 2011-2015 American Community Survey 5-Year estimates program (UCSB, 2017) and employment totals came from the departments of labor in each state, with supplemental counts from the BEA added.

A comparison of household and employment growth rates by County for the 5-year period from 2010 to 2015 demonstrates where the forecasted growth rates in the Model misrepresented the actual growth measured empirically by the 2015 land-use data.

Table 4 shows the differences between the growth forecasts that were used in the Model and the actual growth that occurred from 2010 to 2015, according to the BEA (BEA, 2017).

Table 4 Growth Forecast Differences Between Previous Estimate and 2010 to 2015 BEA

County	Retail	Manufctg	Non-Manufctg	Govnmt	Education
Addison	-1.6%	3.1%	0.1%	-1.0%	3.4%
Bennington	-2.1%	2.2%	-0.4%	0.1%	-0.2%
Caledonia	-0.5%	-1.2%	-0.9%	-0.6%	1.6%
Chittenden	-0.9%	-0.8%	2.3%	2.0%	3.7%
Essex	-2.6%	1.2%	-0.6%	-0.8%	-0.3%
Franklin	0.6%	0.5%	-1.8%	1.4%	7.2%
Grand Isle	-1.4%	0.0%	-1.3%	-1.0%	-0.3%
Lamoille	0.7%	6.0%	-0.1%	-0.2%	-0.3%

County	Retail	Manufctg	Non-Manufctg	Govnmt	Education
Orange	0.1%	3.7%	-0.7%	-0.4%	0.0%
Orleans	-0.8%	5.7%	-0.3%	-0.1%	-0.9%
Rutland	-1.7%	3.3%	0.6%	-2.0%	-0.8%
Washington	-0.5%	0.1%	3.2%	-1.6%	0.2%
Windham	-0.3%	2.5%	-0.5%	-0.3%	-0.9%
Windsor	0.1%	3.0%	2.5%	-0.4%	0.7%
Berkshire (MA)	-0.8%	0.7%	-1.0%	-1.5%	2.8%
Franklin (MA)	-0.8%	1.3%	-1.0%	-1.6%	2.0%
Grafton (NH)	-1.6%	1.7%	-1.0%	-0.9%	-0.2%

Forecasted declines in manufacturing employment had been overestimated by previous forecasting resources, particularly in Lamoille, Orleans, and Orange counties of Vermont, where manufacturing jobs actually *increased* significantly. In these rural communities, unexpected investment by a small number of employers can have a significant effect on growth. For example, in Orleans, the average annual growth rate for manufacturing employment between 2010 and 2015 was 6%, whereas it was forecasted back in 2010 to be about 0%. In the 5-year period, the number of manufacturing jobs in Orleans went from 1,224 to 1,615 (BEA, 2017).

Kimtek is the largest manufacturer of UTV/ATV skid units for ATV rescue in the nation, and it is located in Orleans County. In 2015, Kimtek expanded into a second facility located at 326 Industrial Park Lane in Barton, Vermont. This move tripled the amount of space available for company operations, from the original facility. Kimtek's office headquarters were relocated to the Barton facility as well. Other manufacturers, like Ethan Allen Furniture, in Orleans County may have had similar investments that were unforeseen, but had a significant effect on the 5-year growth in manufacturing employment. Similarly, Lamoille County, Vermont went from 636 to 850 manufacturing jobs between 2010 and 2015. This represents an annual growth rate of 6%, whereas 2010 forecasts expected manufacturing job growth in Lamoille to be stagnant. The total growth 214 jobs in that time period may have been due to an expansion or increased investment by only 1 or 2 employers.

Growth in education employment was underestimated in Chittenden and Franklin Counties, where modest growth forecasts of 0.4% and 0.3%, respectively, did not match the actual growth rates of 4% and 7%. Chittenden County is home to the University of Vermont, with about 3,000 graduates a year, Champlain College, with about 833 graduates, and Saint Michael's College, with about 614 graduates. So it is not surprising that these counties experienced growth, and it is unclear why the forecast resources failed to predict it. This mismatch attests to the need for these large educational institutions to be treated individually, as special generators, for the prediction of growth and trip-generation estimation.

The number of households in Vermont's counties, along with Grafton, NH and Berkshire & Franklin, MA did not grow as rapidly as forecasted between 2010 and 2015. The RMSPE between the forecasted 2015 household counts by County and the actual counts from the 2015 ACS 5-year estimate was 2.5% (UCSB, 2017). For all of the counties in the Model except Addison and Bennington, forecasted annual growth rates were larger than what actually occurred, according to the US Census and the 2015 ACS 5-Year Estimate. The growth forecast for Chittenden County was the closest to actual, overestimating the annual rate by only 0.07%. However, the growth rates forecasted for Caledonia and Essex were overstated by nearly 1% per year, along with the growth rate for Grafton, NH. Using the forecasted growth rates results in a total number of households in the Model region (Vermont, parts of Grafton NH, and parts of Franklin & Berkshire, MA) that exceeds the actual count by almost 2%. More importantly, though, continuing to use the forecasted growth rates would have resulted in a RMSPE of 10.4% for the 2035 forecast.

Although the number of households in the internal Model area (Vermont with 9 Massachusetts towns and 2 New Hampshire towns) between 2010 and 2015 grew by only 0.42%, the structure of the households changed significantly. Generally, households got smaller, as evidenced by the fact that overall population only increased 0.36% over the same time period. One- and 2-person households both increased by 4% in the Model area, whereas 3- and 4-person households decreased by 5% and 7%, respectively. These effects are evident in the changes shown for selected Model towns shown in Table 5.

Table 5 Changes in Household-Type Distributions from 2010 to 2015 for Selected Model Towns

Town	1-person household	2-person household	3-person household	4+ person household
Vergennes city	-11%	37%	6%	-17%
Bennington	32%	19%	-20%	22%

Town	1-person household	2-person household	3-person household	4+ person household
Manchester	38%	2%	-15%	-31%
Burlington	14%	23%	-73%	-32%
Milton	27%	11%	13%	-23%
Williston	24%	29%	-13%	-2%
East Montpelier	98%	21%	-40%	-48%
Waitsfield	39%	-9%	-18%	-2%
Waterbury	6%	19%	-15%	-14%
Woodstock	65%	18%	-10%	-23%
Hanover, NH	10%	28%	-11%	-14%
Lebanon, NH	21%	19%	-6%	-30%
Williamstown, MA	15%	5%	-36%	0%
Greenfield, MA	-2%	50%	-30%	-41%

The new employment growth rates for counties in the Model and the new household types by town were incorporated into the Model in two ways. First, the new employment growth rates for 2010 to 2015 from the BEA were taken to represent the most likely growth trends for all Model forecasts, even those beyond 2015. Next, the 2015 household types by town were incorporated by having them used for any forecast beyond 2015. With these changes in place to represent the actual 2015 conditions, the Model was run and 2015 RMSPE had declined from 46.7% before the changes to 46.5%.

5.3 Validation

The Model is validated by comparing assigned traffic volumes to traffic counts where AADTs are available throughout the state. This comparison is calculated using the root-mean-square percent error:

$$RMSPE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{Y_n^s - Y_n^o}{Y_n^o}\right)^2}$$

Where N is the number of observations, or traffic counts Y^o and Y^s is the corresponding model traffic volume. The goal of the Model improvement task is to maintain an RMSPE under 50%. The current RMSPE of the expanded model after the traffic assignment module is 43.7%. This value represents a slight change in the accuracy of the Model from the best RMPSE of 42.5%. This slight decrease in accuracy was expected since the new TAZs outside of Vermont are not as highly resolved as those inside the state's political boundary, making the trip-generation step less precise. In addition, the NHTS data, upon which the travel behaviors in the Model are built, did not include respondents from outside of Vermont, so it would be expected that the travel behavior of drivers in Massachusetts and New Hampshire differ from those in Vermont slightly.

6 Summary and Recommendations

The Model improvements conducted in Year 9 included the completion an external-travel sub-module. External highway trips in the Model are now routed between Vermont and all urban areas and urban clusters in the northeast U.S. and Quebec. This improvement will afford the Model two new useful features:

1. External trips can be attributed to a specific urban area, as opposed to the previous sub-module, which simply attributed external trips according to their entry point into Vermont
2. External growth can now be forecasted, since growth forecasts are available for urban areas and urban clusters in the northeast U.S.

Using this improved external-travel sub-module, a soft update to year 2015 was also completed. This update incorporated a second validation step at the update year of 2015, and allowed the recalibration of growth rates for all forecasts. The new growth rates use the actual growth that was experienced between 2010 and 2015 in the Model area. New household-type classifications were also captured for 2015 and incorporated into the Model for the 2015 update year and for all forecast years after that.

A TMIP peer review of the Model was conducted in Year 5, resulting in a comprehensive set of recommendations for Model improvements for the years ahead (FHWA, 2013). Selected subtasks are recommended for Year 10 based on the short-term recommendations from the peer review:

- Consider the use of seasonal trip tables in the Vermont Travel Model and analyze all supporting Model data by season to see if a bi-annual Model is feasible
- Identify metrics for emergency scenario comparison to guide model development

7 References

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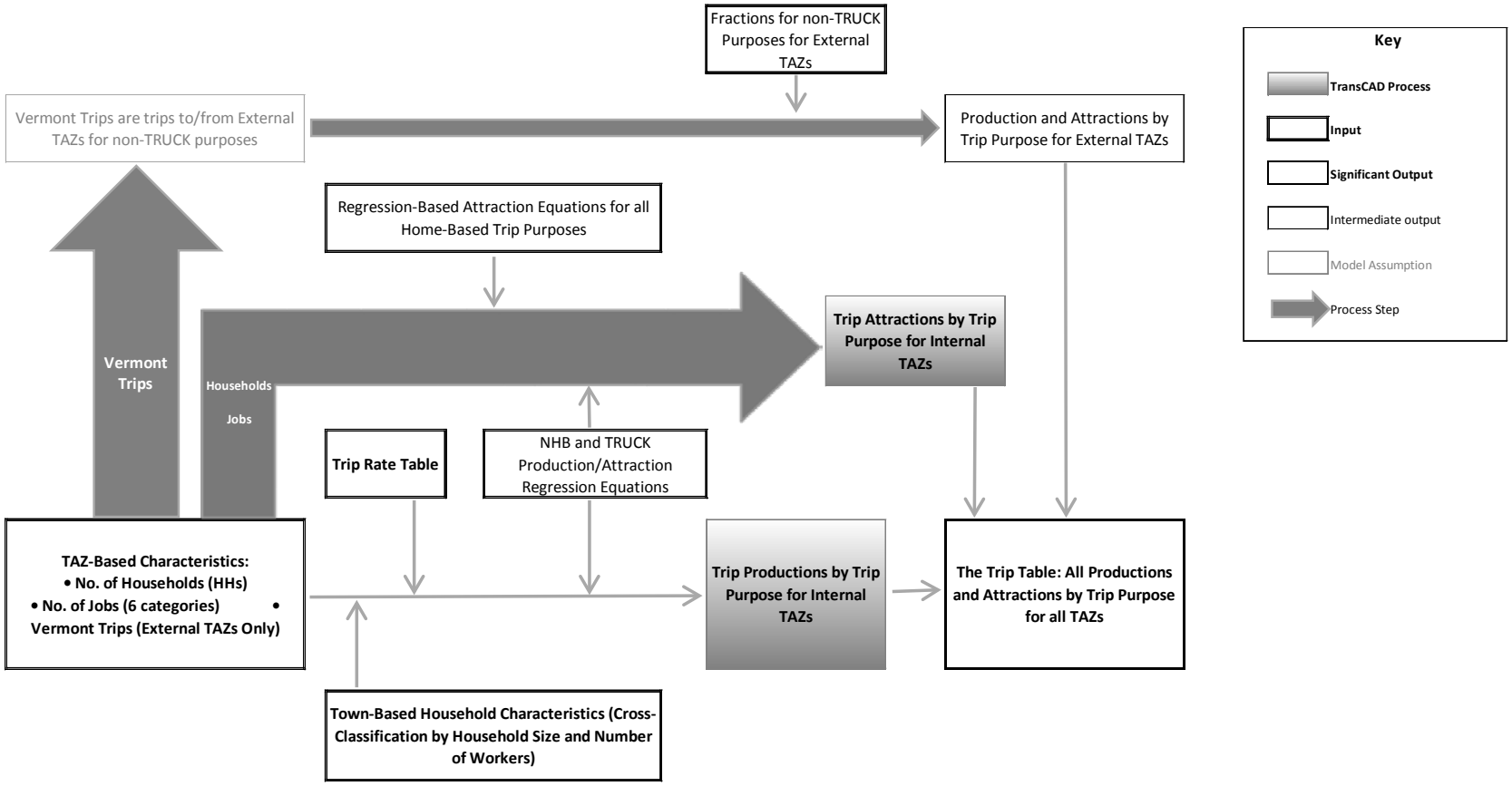
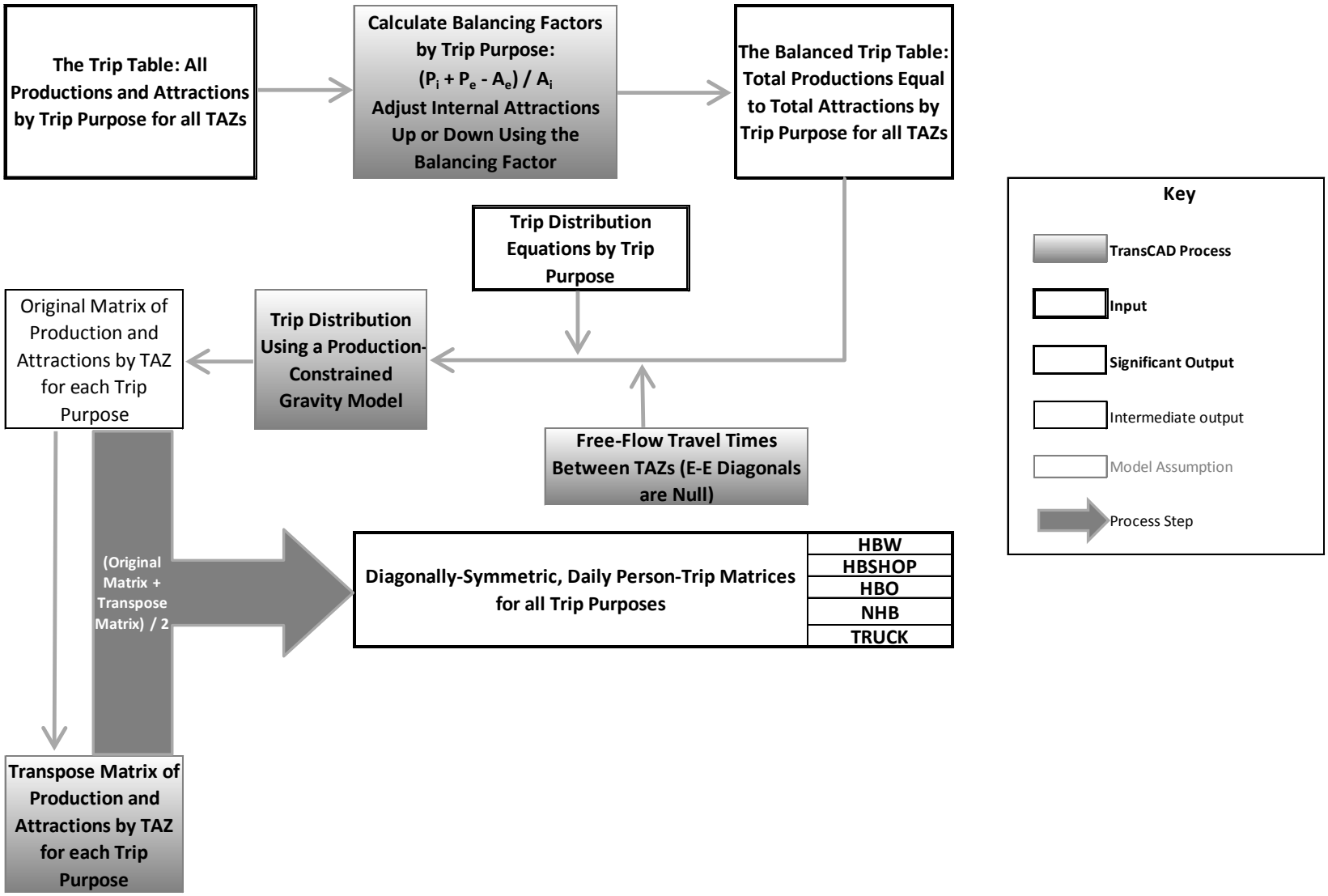
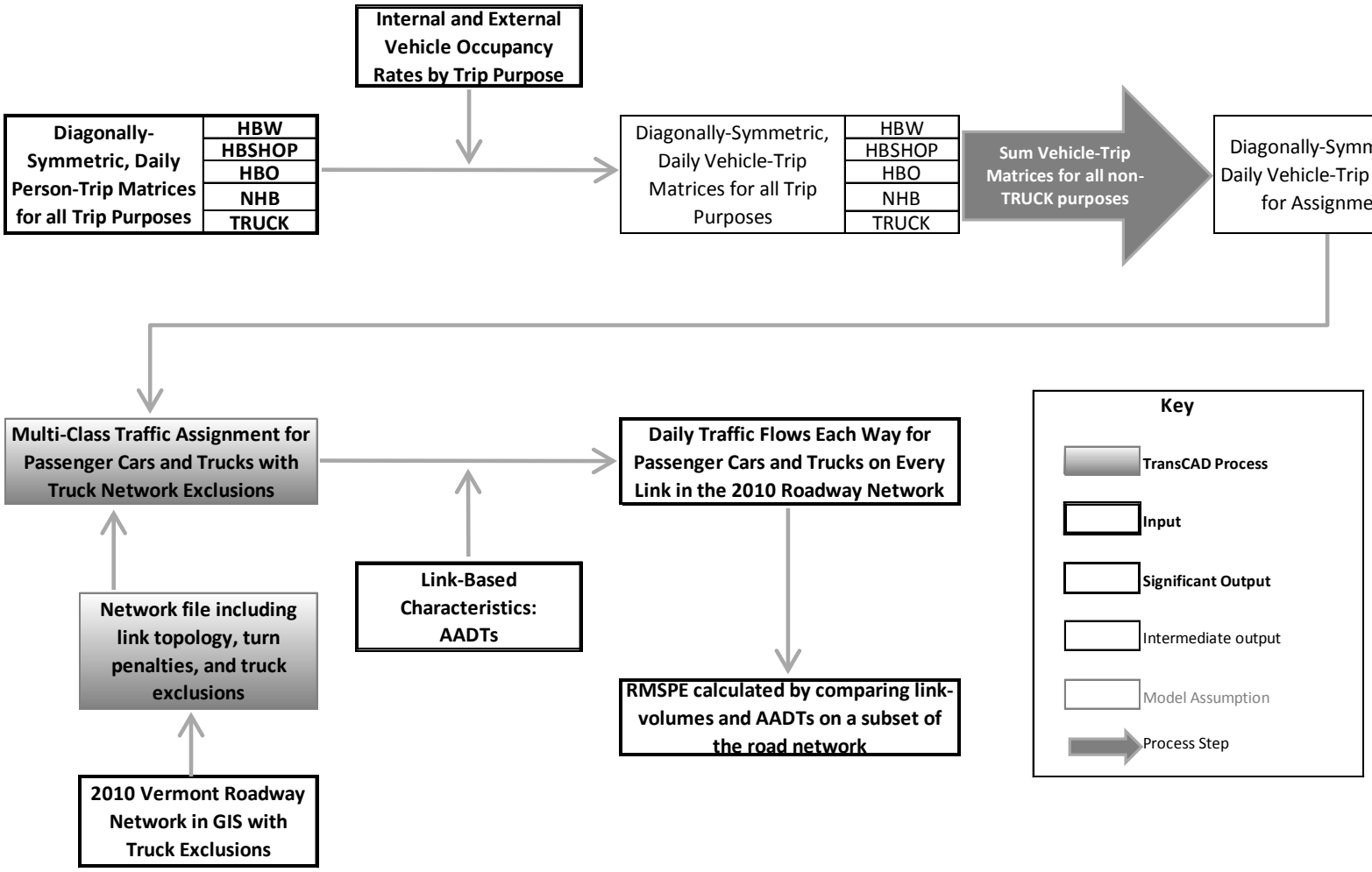
Appendix A – Description of the Model


Fractions for non-TRUCK Purposes for External TAZs
Vermont Trips are trips to/from External TAZs for non-TRUCK purposes
Production and Attractions by Trip Purpose for External TAZs
Regression-Based Attraction Equations for all Home-Based Trip Purposes
Vermont Trips
Households
Jobs
Trip Attractions by Trip Purpose for Internal TAZs
Trip Rate Table
NHB and TRUCK Production/Attraction Regression Equations
TAZ-Based Characteristics:
• No. of Households (HHs)
• No. of Jobs (6 categories)
• Vermont Trips (External TAZs Only)
Trip Productions by Trip Purpose for Internal TAZs
The Trip Table: All Productions and Attractions by Trip Purpose for all TAZs
Town-Based Household Characteristics (Cross-Classification by Household Size and Number of Workers)
Key
TransCAD Process
Input
Significant Output
Intermediate output
Model Assumption
Process Step


The Trip Table: All Productions and Attractions by Trip Purpose for all TAZs
Calculate Balancing Factors by Trip Purpose: $(P_i + P_e - A_e) / A_i$ Adjust Internal Attractions Up or Down Using the Balancing Factor
The Balanced Trip Table: Total Productions Equal to Total Attractions by Trip Purpose for all TAZs
Trip Distribution Equations by Trip Purpose
Original Matrix of Production and Attractions by TAZ for each Trip Purpose
Trip Distribution Using a Production-Constrained Gravity Model
Free-Flow Travel Times Between TAZs (E-E Diagonals are Null)
(Original Matrix + Transpose Matrix) / 2
Diagonally-Symmetric, Daily Person-Trip Matrices for all Trip Purposes
HBW
HBSHOP
HBO
NHB
TRUCK
Transpose Matrix of Production and Attractions by TAZ for each Trip Purpose
Key
TransCAD Process
Input
Significant Output
Intermediate output
Model Assumption
Process Step


Internal and External Vehicle Occupancy Rates by Trip Purpose
Diagonally-Symmetric, Daily Person-Trip Matrices for all Trip Purposes
HBW
HBSHOP
HBO
NHB
TRUCK
Diagonally-Symmetric, Daily Vehicle-Trip Matrices for all Trip Purposes
HBW
HBSHOP
HBO
NHB
TRUCK
Sum Vehicle-Trip Matrices for all non-TRUCK purposes
Diagonally-Symmetric, Daily Vehicle-Trip Matrix for Assignment
Multi-Class Traffic Assignment for Passenger Cars and Trucks with Truck Network Exclusions
Daily Traffic Flows Each Way for Passenger Cars and Trucks on Every Link in the 2010 Roadway Network
Link-Based Characteristics: AADTs
Network file including link topology, turn penalties, and truck exclusions
2010 Vermont Roadway Network in GIS with Truck Exclusions
RMSPE calculated by comparing link-volumes and AADTs on a subset of the road network
Key
TransCAD Process
Input
Significant Output
Intermediate output
Model Assumption
Process Step

Summary

Trip generation (productions and attractions) is estimated for each of five trip-purposes: home-based work, home-based shopping, home-based other (including school travel, social & recreational trips), non-home-based, and truck; and two distance classifications: long-distance and short-distance. Trip generation estimations are based on the 2010 US Census, the 2009 National Household Travel Survey (NHTS), the 2006-2010 American Community Survey (ACS), 2009 data from the Department of Employment and Training of the Vermont Department of Labor (VDOL), and 2009 data from the Bureau of Economic Analysis (BEA). Trip distribution is accomplished using a production-constrained Gravity Model. The traffic assignment module of the Model implements a multi-class user-equilibrium assignment process with two classes – all passenger vehicles and trucks. The multi-class assignment process is used because some of the minor links in the road network are not passable for heavy trucks. Therefore, the multi-class assignment is used to allow passenger cars to use the entire network while preventing trucks from using links where they are prohibited.

The Model includes truck traffic by incorporating "Truck" as a trip purpose. However, no comprehensive freight model has been developed to break truck travel down into medium- and heavy-commercial trucks, and to investigate commodities moved in an average day. Rail transport, passenger transit, and non-motorized travel modes are also not currently part of the functional sub-modules of the Model.

The Model can also be used to run a forecast, run a scenario, and calculate the Network Robustness Indices (NRIs) of links in the forecast-year. The forecast process is initiated by selecting a number of years from 2010 for the forecast to run. The Model then uses default growth rates to increase population and employment in each TAZ to represent the forecast-year growth. Then the Model processes are repeated using the forecasted population and employment. The scenario run implements a select-link analysis (SLA) for a prescribed set of links in the typical traffic assignment step for the forecast-year, outputting a set of towns that utilize the scenario links on a typical day. Then, adjusted capacities and/or travel-times for the scenario links are used in a second traffic assignment step for the forecast-year, to output the effects that the adjustments will have on traffic flows in the region. If the NRI run is selected for the forecast-year, the NRI is calculated for a prescribed set of links.

Trip Generation

The trip-generation module starts by combining the TAZ-based land-use characteristics with the town-based fractions of no. of persons / no. of workers per household cross-classifications to calculate home-based trips produced by each internal TAZ for both long- and short-distance classifications. It then calculates trip attractions for each internal TAZ by purpose and trip-productions for the non-home-based (NHB) purpose using purpose-specific regression equations for both long- and short-distance classifications, each of which utilizes a different set of employment and/or population field(s) from the TAZ characteristics table.

	Long-Distance				Short-Distance				Truck	
Variable	NHB (P/A)	HBW (A)	HB SHOP (A)	HBO (A)	NHB (P/A)	HBW (A)	HB SHOP (A)	HBO (A)	P	A
No. of Households					0.98			2.24	0.19	0.18
Retail Jobs	0.37		0.25		2.84		3.58			
Manufacturing Jobs									0.09	0.23
Non-Manufact. Jobs		0.03		0.08	0.41	0.50		0.13	0.14	0.12
Government Jobs					0.25					0.14
Primary Sch. Jobs										-0.31
University Jobs					0.98				0.19	0.18

For example, the equations for home-based work (HBW) trips attracted are based on all of the employment fields in the TAZ characteristics table, but the equations for home-based shopping (HBSHOP) trips are based solely on the retail employment field. Truck (TRUCK) productions and attractions are calculated from regression equations which utilize a different set of employment and/or population field(s) from the TAZ characteristics table. The distance classification is not applied to the estimation of truck trips in the Model, since our expectation is that the exponential distribution function handles all distances well.

Productions and attractions for zones external to Vermont are calculated differently. First, trips to/from all external TAZs are taken to be the "Vermont Trips" calculated separately from the external trip distribution update, and entered into the TAZ layer. The external vehicle-occupancy rate (as an input) is applied to this total to derive non-TRUCK external person-trips (PTs). Total non-TRUCK external PTs are then subdivided into the other 8 trip purposes (4 main purposes x 2 distance classifications) using the following fractions:

- HBW – short-distance: 10%
- HBW – long-distance: 2%

- HBSHOP – short-distance: 19%
- HBSHOP – long-distance: 3%
- HBO – short-distance: 26%
- HBO – long-distance: 6%
- NHB – short-distance: 28%
- NHB – long-distance: 6%

Ultimately, this process outputs a table of productions and attractions for each of the ten trip purposes in the Model for each of the 943 internal and external zones. However, since the production and attraction estimates for the internal TAZs came from different sources, they do not match. This mismatch is typical for demand-forecasting models where separate regression models are estimated for production and attraction across a full study area with unique predictor variables. Balance factors are calculated as the ratio of trip productions destined for internal zones to the corresponding trip attractions in internal zones by trip purpose. Balancing is accomplished by zone by multiplying the balancing factors by the internal trip attractions only so that they match total productions (internal and external) by trip purpose. The end result is a table of balanced productions and attractions for each of the ten trip purposes in the Model for each zone. Summary statistics of the balanced trip production/attraction table are provided in the following table:

Trip Purpose	Class	Sum	Min	Max	Mean	Std Dev.
HBW-SD	No. of Trips Produced	313,326	0.0	6,249	342	367
HBW-LD		17,512	0.0	500	19	30
HBSHOP-SD		501,825	0.0	9,231	546	643
HBSHOP-LD		27,040	0.0	1,979	29	104
HBO-SD		720,538	0.0	13,010	784	933
HBO-LD		51,888	0.0	2,523	56	136
NHB-SD		598,248	0.0	16,608	619	919
NHB-LD		34,492	0.0	2,510	36	138
TRUCK		92,632	0.0	1,990	105	122
HBW-SD	No. of Trips Attracted	313,326	0.0	12,517	324	647
HBW-LD		17,512	0.0	607	18	39
HBSHOP-SD		501,825	0.0	26,103	519	1,316
HBSHOP-LD		27,040	0.0	1,979	28	109
HBO-SD		720,538	0.0	14,716	746	952

Trip Purpose	Class	Sum	Min	Max	Mean	Std Dev.
HBO-LD		51,888	0.0	2,523	54	144
NHB-SD		598,248	0.0	16,608	619	919
NHB-LD		34,492	0.0	2,510	36	138
TRUCK		92,632	0.0	1,240	107	110

Trip Distribution

The trip-distribution sub-module takes the balanced trip table, a matrix of free-flow travel times between TAZs and a set of impedance functions or friction factors to develop a matrix of trips between all zones. For short-distance trips, impedance functions are used but for long-distance trips the estimated impedance functions have been turned into a table of friction factors for HBO and NHB trips, so long-distance trips are prevented from being distributed to TAZs closer than 40 miles. The set of impedance functions used to distribute short-distance trips is:

Trip Purpose	Impedance Function		a	b	c
HBW-SD	Gamma	$f(t_{ij}) = a \cdot t_{ij}^{-b} \cdot e^{-c(t_{ij})}$	0.07	0.86	0.095
HBSHOP-SD	Gamma	$f(t_{ij}) = a \cdot t_{ij}^{-b} \cdot e^{-c(t_{ij})}$	0.099	1.15	0.128
HBO-SD	Gamma	$f(t_{ij}) = a \cdot t_{ij}^{-b} \cdot e^{-c(t_{ij})}$	0.029	1.20	0.126
NHB-SD	Gamma	$f(t_{ij}) = a \cdot t_{ij}^{-b} \cdot e^{-c(t_{ij})}$	0.11	0.75	0.116
TRUCK	Exponential	$f(t_{ij}) = e^{-c(t_{ij})}$			0.065

The impedance functions used to calculate friction-factors for long-distance trips are:

Trip Purpose	Impedance Function		a	b	c
HBW-LD	Gamma	$f(t_{ij}) = a \cdot t_{ij}^{-b} \cdot e^{-c(t_{ij})}$	0.07	0.86	0.095
HBSHOP-LD	Gamma	$f(t_{ij}) = a \cdot t_{ij}^{-b} \cdot e^{-c(t_{ij})}$	0.099	1.15	0.128
HBO-LD	Exponential	$f(t_{ij}) = e^{-c(t_{ij})}$			0.012
NHB-LD	Exponential	$f(t_{ij}) = e^{-c(t_{ij})}$			0.011
TRUCK	Exponential	$f(t_{ij}) = e^{-c(t_{ij})}$			0.065

The Model was found to perform better when the distance-classification threshold was not applied to the distribution of HBW or HBSHOP trips. Therefore, the impedance functions for long- and short-distance trips for these purposes are identical.

The result of this step is a matrix of productions and attractions between all zones. Since the Model is a daily model, all trips are assumed to return, meaning that all trips originating in one zone and destined for another must

also originate in the destination zone and terminate in the origin zone. This assumption requires that the final matrix be diagonally symmetric. To accomplish this, the matrix is added to its transpose and then all cells are halved. The result is a diagonally-symmetric O-D matrix of PTs.

In the past, the O-D matrix of PTs was reduced by the expected transit demand before allocating the remaining trips to passenger vehicles. However, the existing matrix of transit demand may date back as far as 1997, so no defensible data source for transit demand exists, and the 2009 NHTS does not support the development of a full O-D matrix of transit demand statewide. Therefore, transit demand is no longer considered directly in the Model. Instead, the full O-D matrices resulting from the trip-distribution step are divided by a vehicle-occupancy to convert them from person-trips to passenger vehicle-trips. The vehicle occupancies currently used in the Model, derived from the 2009 NHTS, are:

Trip Purpose	Internal Trips	Internal to External & External to Internal Trips
Home-Based Work – SD	1.12	1.05
Home-Based Shopping – SD	1.48	1.79
Home-Based Other – SD	1.75	2.00
Non-Home-Based - SD	1.53	1.52
Home-Based Work – LD	1.38	1.16
Home-Based Shopping – LD	1.71	3.06
Home-Based Other – LD	1.57	1.95
Non-Home-Based – LD	1.43	1.94
Truck	1.00	1.00

Traffic Assignment

The final matrix, including all passenger vehicle-trips (all of the non-TRUCK matrices summed) and truck trips (all TRUCK trips), is assigned to the road network in the traffic assignment sub-module. Free-flow travel speed on each link is assumed to be 5 miles per hour over the speed limit, and the user-equilibrium multi-class traffic assignment is used. The multi-class assignment allows trucks and passenger vehicles to be assigned to a separate road network, with the truck network incorporating exclusions wherever trucks are prohibited on the road network. The assignment results in daily traffic flows in each direction for passenger vehicles and trucks on every link in the 2010 road network, as well as the RMSPE calculated by comparing these link volumes with AADTs on a subset (2,240 of 5,670) of the links in the network. Links excluded from the calculation include:

- Centroid connectors
- Links representing roadways for which an AADT was not determined
- Links with high variations in directional flow (the AADT is not distinguished by direction of flow)

The current RMSPE of the Model run for its base-year of 2010 is 43.7%.

Forecasting, Scenario Modeling, and Critical Link Analysis

Forecasting for scenario modeling in the Vermont Travel Model is accomplished using fixed growth rates derived from statewide and local economic forecasts for employment and population. Employment growth by sector & county and household growth by county are:

County	Retail	Manufacturing	Non-Manufacturing	Government	Education	Households
Addison	-0.007	0.02	0.009	-0.008	0.037	0.004
Bennington	-0.014	0.01	0.002	0.001	0.001	0.002
Caledonia	0.004	-0.019	-0.001	-0.004	0.019	-0.004
Chittenden	0.000	-0.008	0.032	0.022	0.041	0.005
Essex	-0.019	0.000	-0.002	-0.008	0.000	-0.008
Franklin	0.015	0.005	-0.01	0.016	0.075	0.002
Grand Isle	-0.004	0.000	-0.001	-0.008	0.000	0.004
Lamoille	0.018	0.06	0.013	0.000	0.000	0.003
Orange	0.01	0.031	0.001	-0.002	0.003	0.004
Orleans	0.001	0.057	0.006	0.001	-0.006	-0.002
Rutland	-0.01	0.021	0.012	-0.018	-0.005	-0.004
Washington	0.002	-0.005	0.039	-0.014	0.005	-0.004
Windham	0.003	0.013	0.000	-0.006	-0.006	-0.002
Windsor	0.008	0.018	0.03	-0.006	0.01	-0.002
Berkshire (MA)	0.001	0.004	0.005	-0.003	0.036	-0.003
Franklin (MA)	0.001	0.01	0.005	-0.004	0.028	-0.002
Grafton (NH)	-0.011	0.022	0.01	-0.01	0.018	-0.005

Using these annual growth rates, any forecast-year can be selected and run. When a forecast-year is selected, the Model simply recalculates TAZ-level employment and households for the forecast year by applying the growth rate by county, and runs the Model using the updated TAZ characteristics. For forecasts beyond 2025, a modified road network is used for the traffic assignment which includes new roadways expected to be completed by then. For forecasts beyond 2035, additional projects are added to the 2025 network for the forecast-year run. Any Model outputs available for the base-year are available for the forecast-year, and the Model automatically calculates the change in traffic flows on each link between the base-year and the forecast-year.

The Model can also be used run a scenario for a selected set of scenario-links in the forecast-year. For a scenario run, the link layer is modified with a "1" in the "Scenario?" field for any links that will be modified as part of the scenario. Scenario-specific capacity and travel-time fields are also provided to enter the adjusted values that will be used to simulate the scenario. Then, if the "Run a forecast scenario" checkbox is checked, the scenario run first implements a SLA in the assignment step for the forecast-year, outputting a set of towns that utilize the scenario link(s) on a typical day. Then the assignment step is repeated using the adjusted capacities and/or travel-times for the scenario link(s) for the forecast-year. The traffic flow outputs of the scenario assignment can then be compared to the outputs of the standard assignment for the forecast year, indicating the effects that the adjustments arte expected to have on traffic flows in the region.

If the "Run the forecast NRI" checkbox is checked, the NRI is calculated for a prescribed set of links. A selection tool is opened for the user to specify the capacity reduction to apply, and the subset of links to apply it to, and an output file is created with the NRI values for each link specified. For additional information on the NRI process for determining link criticality, refer to Sullivan et. al., (2010).

Appendix B - Users' Guide

Model Platform and Files

The Vermont Travel Model is a GISDK scripted "macro" in the TransCAD software platform that invokes many of TransCAD's built-in menu-driven processes to simulate a typical day of travel in Vermont:

- Trip Production / Cross-Classification…
- Trip Attraction / Apply a Model…
- Trip Distribution / Gravity Application… & Gravity Calibration…
- Static Traffic Assignment / Multi-Modal, Multi-Class Assignment…

The Model consists of the geographic layers representing the road network and the TAZ layer saved in TransCAD's native "map" (*.map) file format, along with TransCAD's native "network" (*.net) file representing the road network topology, and its complementary "turn penalty" table representing prohibited turns in the network topology. Binary-format input tables ("*.bin") used by the Model include:

- Cross-classification of household types by number of workers and number of household members for each Vermont town
- Trip-rate table by number of workers and number of household members
- Forecast annual growth-rates for employment and population by County
- Coefficients of the regression equations by trip purpose for trip-attraction calculations
- Constants for the gamma and exponential trip-distribution equations by trip purpose
- Friction-factors for long-distance classifications by trip purpose

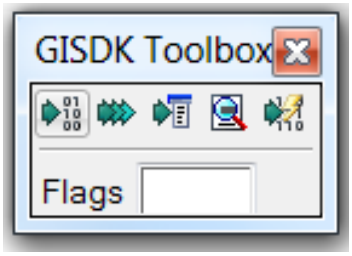
Future road-network configurations are provided for 2105, 2025 and 2035 in TransCAD's network (*.net) file format to enforce the future topology for forecast-year simulations.

The names of each of these files are provided in the following table:

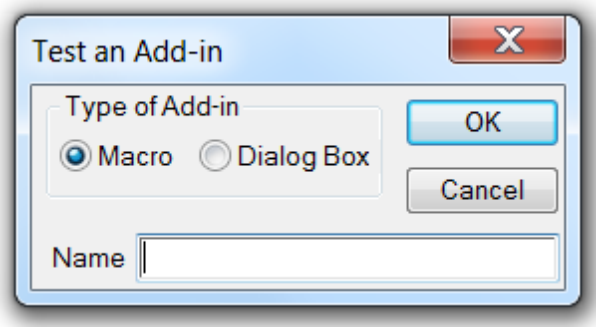
File Description	Name	Type
Native map file which opens the road network, the TAZ layer, and the network topology	Vermont Travel Model	TransCAD map (.map)

File Description	Name	Type
Road network geographic file	VT Region Links	TransCAD standard geographic file (.dbd)
TAZ layer geographic file	Model TAZs	.dbd
Network topology file representing the road network in the base year	by_net	TransCAD network (.net)
Complementary "turn penalty" table representing prohibited turns in the network topology	TurnPenalties	Binary table (.bin)
Cross-classification of household types by number of workers and number of household members for each Vermont town in 2009	HHTypeByTown_2009	.bin
Cross-classification of household types by number of workers and number of household members for each Vermont town in 2015	HHTypeByTown_2015	.bin
Trip-rate table by number of workers and number of household members	VTM Trip Rate Table	.bin
Forecast annual growth rates for employment and population by County	Growth Rates	.bin
Coefficients of the regression equations by trip purpose for trip attraction calculations	RegressionCoefficients	.bin
Constants for the gamma and exponential trip distribution equations by trip purpose	TripDistImpedanceSpecs	.bin
Friction factors for long-distance classifications by trip purpose	LDFrictionFactors	.bin
Network file representing the topology of the road network in 2015	fymodelnet (distinguished by its location, in the *2015 Update Year* folder)	.net
Network file representing the topology of the road network in 2025	fymodelnet (distinguished by its location, in the *2025 Forecast Year* folder)	.net
Network file representing the topology of the road network in 2035	fymodelnet (distinguished by its location, in the *2035 Forecast Year* folder)	.net

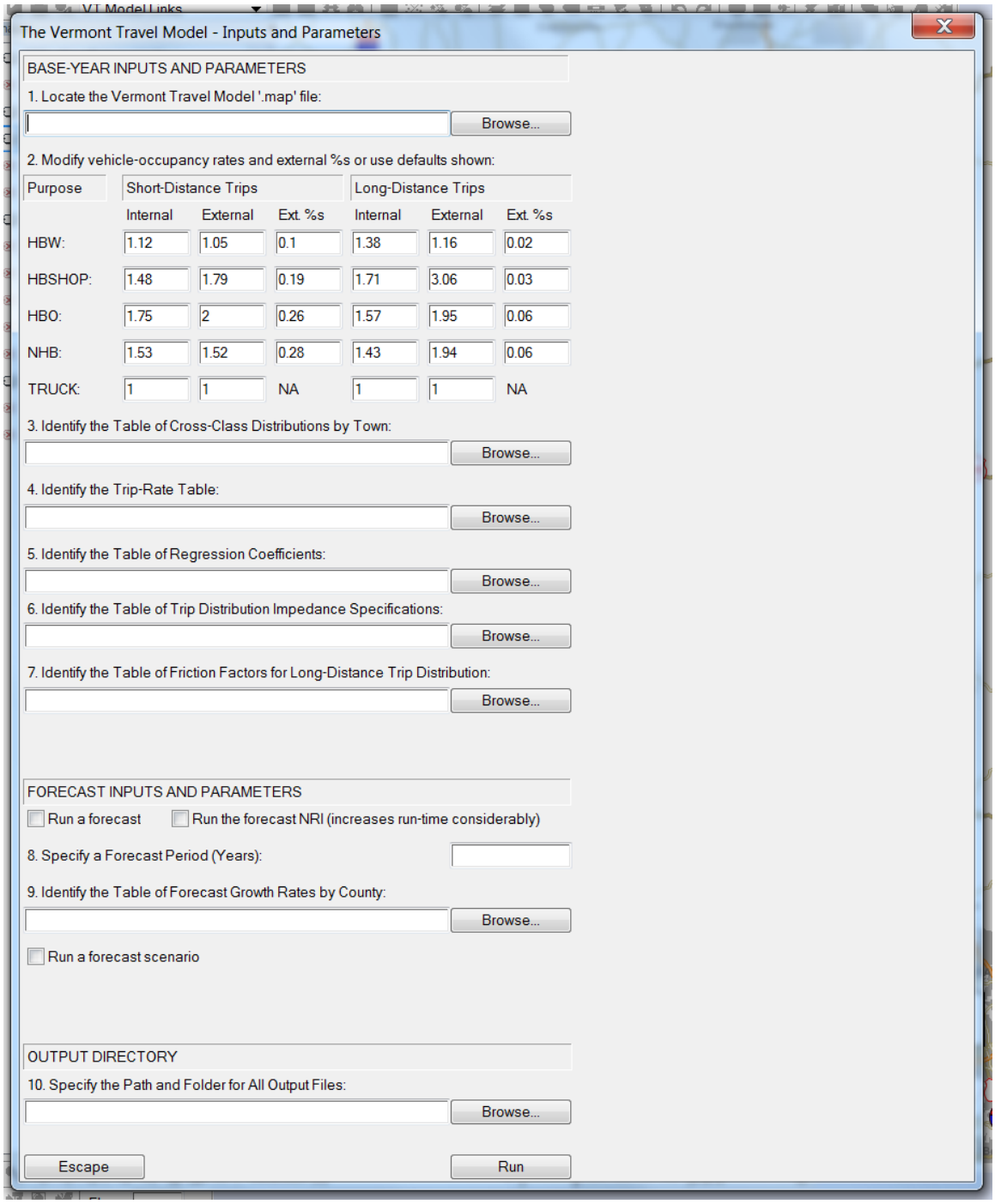
The new menu interface is called up by activating the GISDK Toolbox:



Selecting the button on the far left (a single arrow pointing to 0s and 1s) allows the user to compile the Model code, then selecting the next button to the right (three overlapping arrows) opens the dialog box used to open the initial Model menu



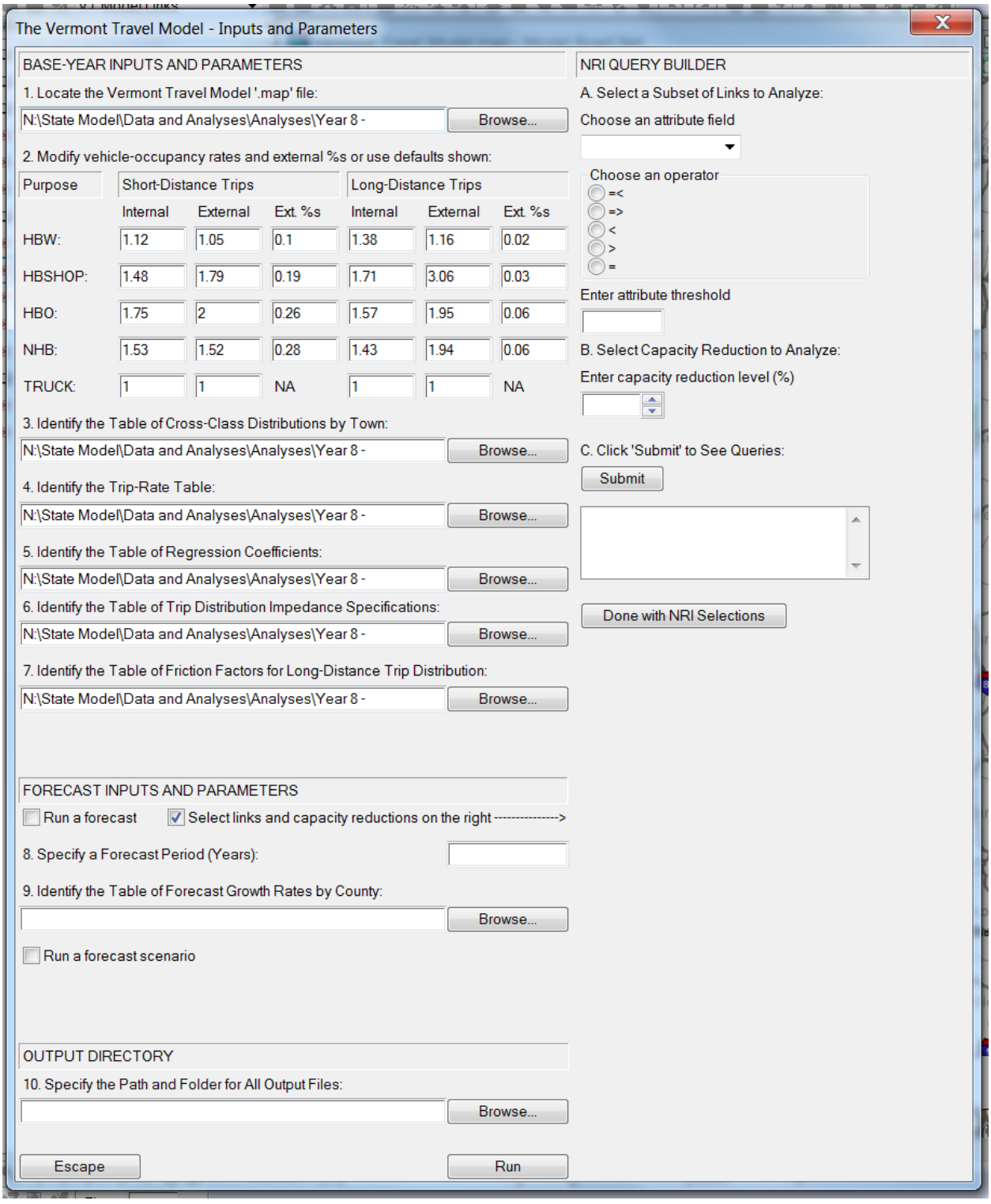
To open the initial Model menu, the user enters “The Vermont Travel Model” (leaving the “Macro” radio button selected) and clicks OK. Once this is done, the initial Model menu appears:



The menu contains ten (10) items and three (3) checkboxes for the user to enter for the Model run:

1. The Vermont Travel Model ".map" file – currently called "Vermont Travel Model.map" and contains the TAZ layer, the road network layer, and the base-year network file (.net)

2. Vehicle-occupancy rates and external fractions – defaults shown are taken from the 2009 NHTS, but they can be altered for a scenario run
3. Table of Cross-Class Distributions by Town – currently called "HHTypeByTown_2009.bin" or "HHTypeByTown_2015.bin" and contains the breakdown of household-structures, by workers and members, for each town in the state
4. Trip-Rate Table – currently called "VTM Trip Rate Table.bin" and contains the trip-production rates for each of the household structures in the breakdown in "HHTypeByTown_2009.bin" or "HHTypeByTown_2015.bin"
5. Table of Regression Coefficients – currently called "RegressionCoefficients.bin" and contains the coefficients for regression equations used to calculate trip productions and attractions
6. Table of Coefficients for Trip Distribution Functions – currently called "TripDistImpedanceSpecs.bin" and contains the coefficients to be used in the impedance functions for short-distance trip distribution to determine the destinations of trips from each TAZ
7. Table of Friction-Factors for Long-Distance Trip Distribution – currently called "LDFrictionFactors.bin" and contains the friction factors corresponding to the impedance functions for long-distance trip distribution
8. Forecast Period – user-specified number of years to forecast travel to, assuming a base year of 2010 (any integer higher than 5)
    a. "Run a forecast" checkbox – check to run the forecast
    b. "Run the forecast NRI" checkbox – check to open the NRI specification dialog box and run the NRI for the forecast year:



9. Table of Forecast Growth Rates – currently called “Growth Rates.bin” and contains the annual growth rates for each employment category and households by Vermont County

   a. “Run a forecast scenario” checkbox – check to implement the scenario run steps for the forecast year

10. Output Directory – user-specified directory where output files will be saved after the Model run

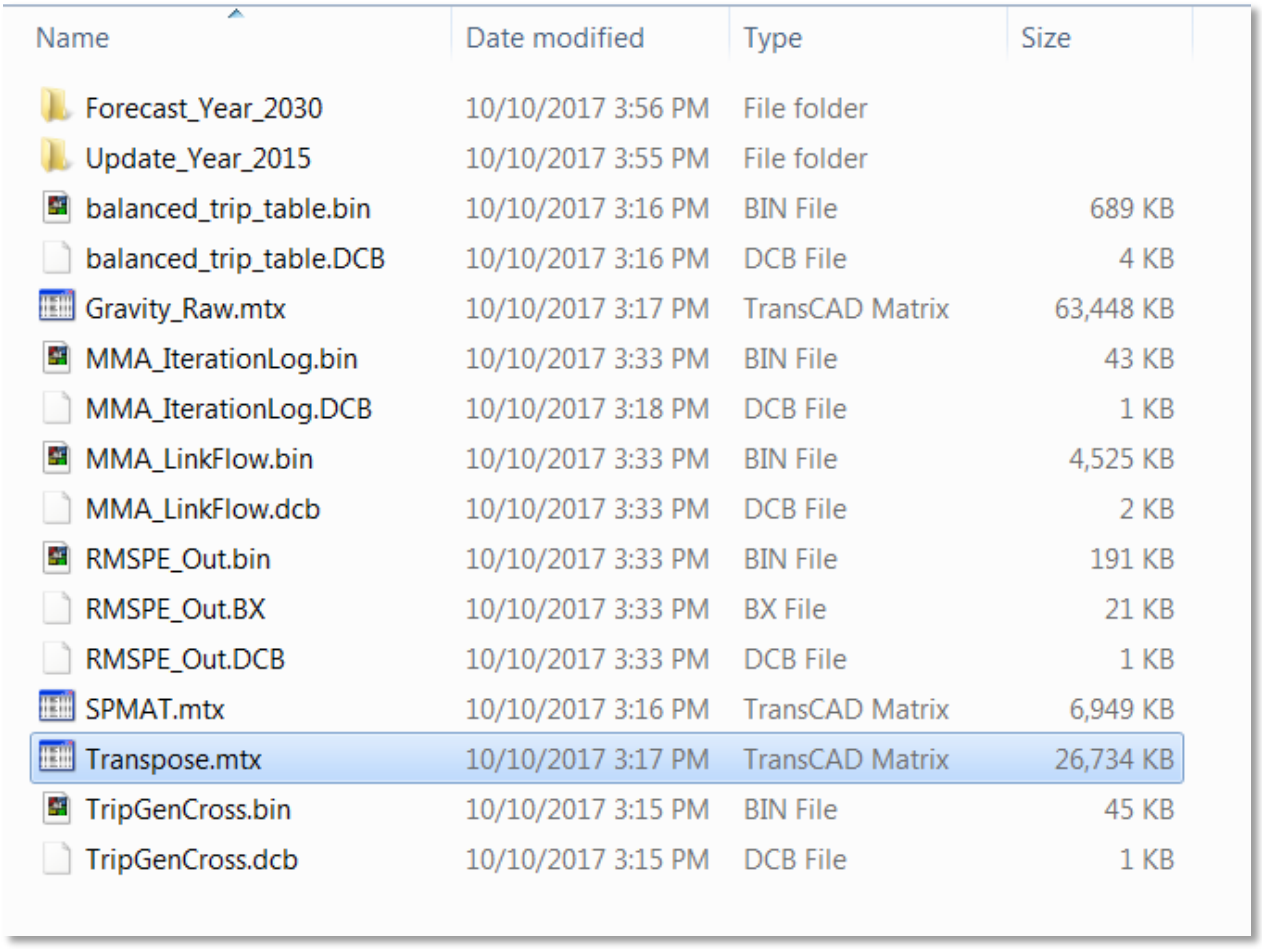
This full specification of the Model input files means that the files will not have to be in a specific location on the user’s computer for the Model to run. The input files can be anywhere. As long as a path and filename is provided for each input file in this menu, the Model will run successfully.

The forecast-period specification allows the Model to be run to any forecast year the user chooses, creating a sub-folder in the output folder identified by the forecast-year with Model outputs for that year. To run multiple forecasts, the user can repeat the Model run with a new forecast-period, and a new forecast-output folder will be created and populated.

Once all of the items are populated, the Model is initiated by clicking the “Run” button at the bottom right corner of the Initial Model Menu.

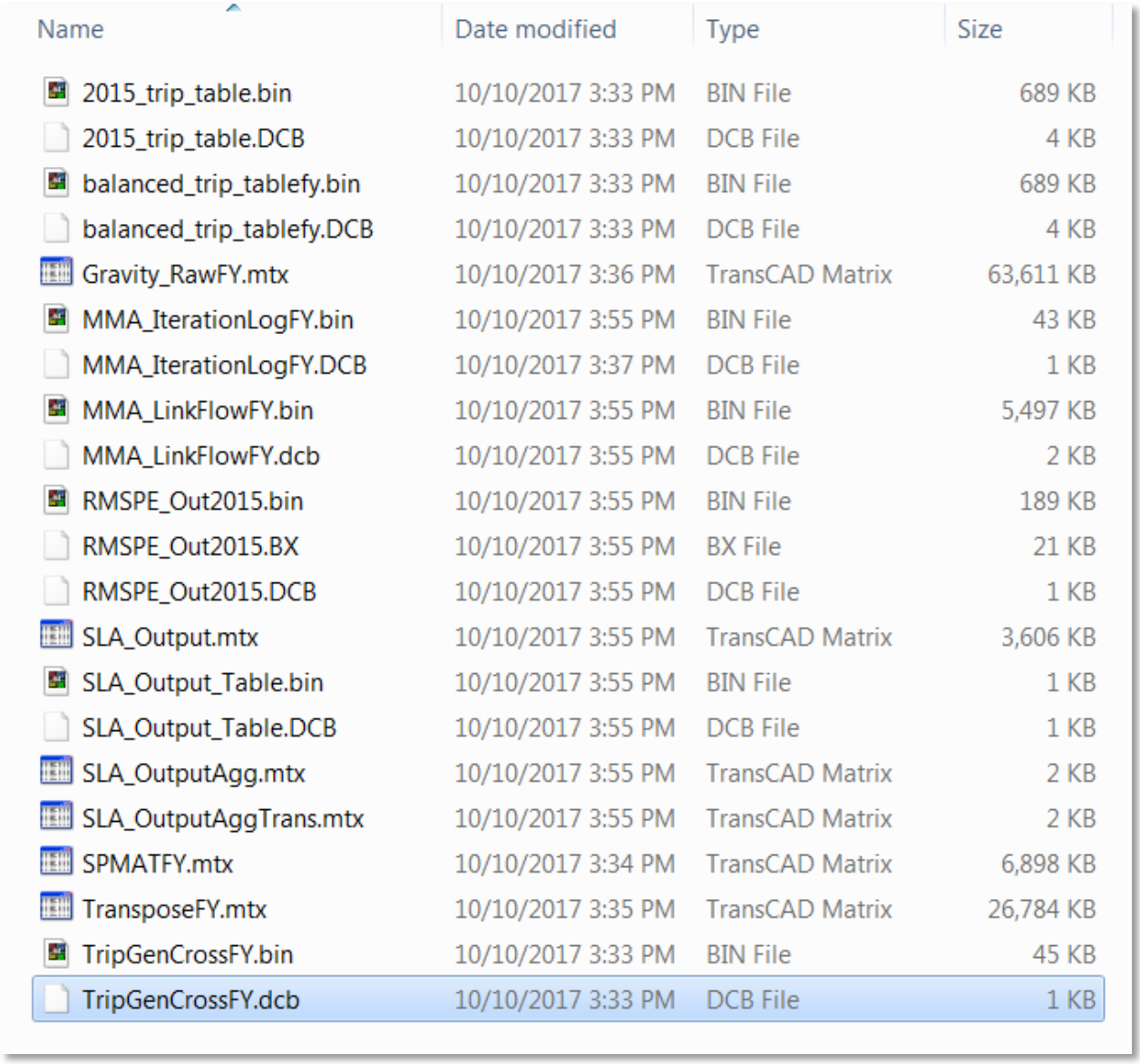
Output Files

All Model output files are placed in the folder identified on the initial menu by the user. An example of a full set of output files from a Model run includes:



Name	Date modified	Type	Size
Forecast_Year_2030	10/10/2017 3:56 PM	File folder	
Update_Year_2015	10/10/2017 3:55 PM	File folder	
balanced_trip_table.bin	10/10/2017 3:16 PM	BIN File	689 KB
balanced_trip_table.DCB	10/10/2017 3:16 PM	DCB File	4 KB
Gravity_Raw.mtx	10/10/2017 3:17 PM	TransCAD Matrix	63,448 KB
MMA_IterationLog.bin	10/10/2017 3:33 PM	BIN File	43 KB
MMA_IterationLog.DCB	10/10/2017 3:18 PM	DCB File	1 KB
MMA_LinkFlow.bin	10/10/2017 3:33 PM	BIN File	4,525 KB
MMA_LinkFlow.dcb	10/10/2017 3:33 PM	DCB File	2 KB
RMSPE_Out.bin	10/10/2017 3:33 PM	BIN File	191 KB
RMSPE_Out.BX	10/10/2017 3:33 PM	BX File	21 KB
RMSPE_Out.DCB	10/10/2017 3:33 PM	DCB File	1 KB
SPMAT.mtx	10/10/2017 3:16 PM	TransCAD Matrix	6,949 KB
Transpose.mtx	10/10/2017 3:17 PM	TransCAD Matrix	26,734 KB
TripGenCross.bin	10/10/2017 3:15 PM	BIN File	45 KB
TripGenCross.dcb	10/10/2017 3:15 PM	DCB File	1 KB

In this example, the “Run a forecast” checkbox was checked and a 20-year forecast was run, so the forecast-year output folder is automatically named “Forecast_Year_2030”. The “Update_Year_2015” folder is now automatically produced to show the Model outputs for 2015. Clicking on the update-year folder reveals additional output files:



Name	Date modified	Type	Size
2015_trip_table.bin	10/10/2017 3:33 PM	BIN File	689 KB
2015_trip_table.DCB	10/10/2017 3:33 PM	DCB File	4 KB
balanced_trip_tablefy.bin	10/10/2017 3:33 PM	BIN File	689 KB
balanced_trip_tablefy.DCB	10/10/2017 3:33 PM	DCB File	4 KB
Gravity_RawFY.mtx	10/10/2017 3:36 PM	TransCAD Matrix	63,611 KB
MMA_IterationLogFY.bin	10/10/2017 3:55 PM	BIN File	43 KB
MMA_IterationLogFY.DCB	10/10/2017 3:37 PM	DCB File	1 KB
MMA_LinkFlowFY.bin	10/10/2017 3:55 PM	BIN File	5,497 KB
MMA_LinkFlowFY.dcb	10/10/2017 3:55 PM	DCB File	2 KB
RMSPE_Out2015.bin	10/10/2017 3:55 PM	BIN File	189 KB
RMSPE_Out2015.BX	10/10/2017 3:55 PM	BX File	21 KB
RMSPE_Out2015.DCB	10/10/2017 3:55 PM	DCB File	1 KB
SLA_Output.mtx	10/10/2017 3:55 PM	TransCAD Matrix	3,606 KB
SLA_Output_Table.bin	10/10/2017 3:55 PM	BIN File	1 KB
SLA_Output_Table.DCB	10/10/2017 3:55 PM	DCB File	1 KB
SLA_OutputAgg.mtx	10/10/2017 3:55 PM	TransCAD Matrix	2 KB
SLA_OutputAggTrans.mtx	10/10/2017 3:55 PM	TransCAD Matrix	2 KB
SPMATFY.mtx	10/10/2017 3:34 PM	TransCAD Matrix	6,898 KB
TransposeFY.mtx	10/10/2017 3:35 PM	TransCAD Matrix	26,784 KB
TripGenCrossFY.bin	10/10/2017 3:33 PM	BIN File	45 KB
TripGenCrossFY.dcb	10/10/2017 3:33 PM	DCB File	1 KB

Clicking on the forecast-year folder reveals a final set of output files for the forecast year similar to those shown for the update year. The following table provides descriptions of each of the output files generated by a typical Model run.

File Name	File Description
TripGenCross.bin (and matching *.dcb)	A fixed-format binary table of trip productions by TAZ for the 6 home-based trip purposes
trip_table.bin (and matching *.dcb)	A fixed-format binary table of trip productions and attractions by TAZ for the 8 non-TRUCK trip purposes
SPMAT.mtx	A TransCAD matrix file consisting of the shortest travel-time paths between all TAZs in the Model

File Name	File Description
Gravity_Raw.mtx	A TransCAD matrix file consisting of 19 matrix cores with the output of the trip distribution step for each of the 9 trip purposes in person-trips and vehicle-trips, concluding with a core of the diagonally-symmetric total vehicle-trips for the traffic assignment
Transpose.mtx	A TransCAD matrix file which is the transpose of the assymetric total vehicle-trip matrix, used to make the diagonally-symmetric matrix of total vehicle trips
MMA_LinkFlow.bin (and matching *.dcb)	A fixed-format binary table of link flows resulting from the multi-class traffic assignment for every link in the Model network
RMSPE_Out.bin (and matching *.dcb)	A fixed-format binary table of squared errors between the link flows and 2010 AADTs every link in the Model network that has a 2010 AADT, and the RMSPE of the Model run
RMSPE_Out2015.bin (and matching *.dcb)	A fixed-format binary table of squared errors between the link flows and 2015 AADTs for every link in the Model network that has a 2015 AADT, and the RMSPE of the Model run
TripGenCrossFY.bin (and matching *.dcb)	A fixed-format binary table of **forecast-year** trip productions by TAZ for the 6 home-based trip purposes
YYYY_trip_table.bin (and matching *.dcb)	A fixed-format binary table of **forecast-year** trip productions and attractions by TAZ for the 8 non-TRUCK trip purposes
SPMATFY.mtx	A TransCAD matrix file consisting of the shortest travel-time paths between all TAZs in the Model for the **forecast-year network**
Gravity_RawFY.mtx	A TransCAD matrix file consisting of 19 matrix cores with the output of the trip distribution stepfor the **forecast-year** for each of the 9 trip purposes in person-trips and vehicle-trips, concluding with a core of the diagonally-symmetric total vehicle-trips for the traffic assignment
TransposeFY.mtx	A TransCAD matrix file which is the transpose of the assymetric total vehicle-trip matrix for the **forecast-year**, used to make the diagonally-symmetric matrix of total vehicle trips
MMA_LinkFlowFY.bin (and matching *.dcb)	A fixed-format binary table of link flows resulting from the multi-class traffic assignment in the **forecast-year** for every link in the Model network

The RMSPE output table was added to the Model to help see the RMSPE and link-specific squared errors (SE) more efficiently. These statistics are useful for validating the Model, so having them produced in a stand-alone output table allows the Model to be re-estimated and/or updated more efficiently.

When the "Run a forecast scenario" and "Run the forecast NRI" checkboxes are checked, additional output files can be expected in the forecast-year output folder. A list and description of the additional output files are provided in the following table:

File Name	File Description
SLA_Output.mtx	A TransCAD matrix file with the SLA output for the scenario links in the **forecast-year**, used to make SLA_OutputAgg.mtx
SLA_OutputAgg.mtx (and its transpose SLA_OutputAggTrans.mtx)	A TransCAD matrix file (and its transpose) with the SLA output for the scenario links in the **forecast-year**, aggregated to towns (instead of TAZs) using the "Aggregate Matrix" macro, used to make SLA_Output_Table.bin
SLA_Output_Table.bin (and SLA_Output_Table.dcb)	A fixed-format binary table of link flows for all towns that use the scenario-links on a typical day resulting from the multi-class traffic assignment in the **forecast-year**
MMA_LinkFlowSC.bin (and MMA_LinkFlowSC.dcb)	A fixed-format binary table of link flows resulting from the multi-class traffic assignment in the **forecast-year** for every link in the Model network with scenario-specific capacities and travel times
FYNRI_Output.bin (and FYNRI_Output.dcb)	A fixed-format binary table of NRIs resulting from the NRI calculation in the **forecast-year** for every link specified in the NRI Specification Dialog Box

Model outputs in the output folder get over-written each time the Model is run, so this information should be saved to a new folder each time the Model is run. If a different forecast-year is used, the old forecast-year outputs will remain in the old forecast-year output folder, so in that case there is no need to save the outputs separately to a new folder.