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Identifying Network Representation Issues with the Network Trip Robustness

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Disclaimer

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1 Introduction

The purpose of this study was to evaluate the effects of road-network representation on the application of the Network Robustness Index (NRI), using the Chittenden County Regional Transportation Model. The results are expected to improve the requirements for how a road network must be represented for an effective application of the NRI. This work was performed under Year 2 of UVM Transportation Research Center (TRC) Signature Project 1H – Network Robustness Index: A Comprehensive Spatial-Based Measure for Transportation Infrastructure Management. Funding for this work comes from the USDOT through the University Transportation Center (UTC) at the University of Vermont.

Signature Project 1 is an investigation of the applicability of integrated land-use and transportation models, but it also includes the development of a series of metrics intended to measure global properties of transportation networks for scenario comparisons. This report advances the application of the tool designed to assess the robustness of transportation systems - the NRI.

The NRI is distinguished from other disruption measures and indices in that it accounts for connectivity, link-capacity, network demand, and the presence of isolating links (really a special case of low connectivity) (Sullivan et. al., 2009a). It is proposed as a preferable method for ranking network links over the volume-to-capacity (v/c) ratio and similar local measures. To focus on a network link with a high v/c is to ignore the importance of that link to traffic not using the link or traffic that would re-route without that link. The NRI accounts for the importance of each link to the entire network, making it a more equitable method of determining critical links in the network.

A pilot application of the NRI was performed on the road network of the Chittenden County Metropolitan Planning Organization (CCMPO) (Sullivan et. al., 2010a), and this study builds on that application. The CCMPO represents the 18 municipalities in Chittenden County, Vermont. Serving about 145,000 people (approximately 25% of the state's population), the CCMPO is Vermont's only MPO. As a small-to-medium sized MPO, the CCMPO includes both urban and rural areas in its 537 square miles. The CCMPO road network is part of the CCMPO Regional Transportation Model which was created by Resource Systems Group, Inc. of White River Junction, Vermont (CCMPO, 2008).

As expected, the travel demand model used in the pilot application did not include all of the roads in the County. In particular, many minor roads and local streets are excluded and represented in aggregate by centroid connectors. The focus of this study is the tendency for seemingly insignificant roads and streets to provide significant robustness gains since they can offer critical alternative routes during relatively minor disruption events.

2 The Network Robustness Index and the Network Trip Robustness Methodology

The NRI is the increase in total vehicle-hours of travel (VHTs) on the transportation network resulting from the disruption of a given link. Therefore, the index is link-specific. First, total VHTs when all links are present and operational in the network is calculated for the base-case scenario. The total VHTs are a system-wide, travel time cost:

$$c = \sum_{i \in I} t_i x_i$$

Where t_i is the travel time across link i, in minutes per trip, and x_i is the flow on link i at user equilibrium. I is the set of all links in the network. Second, the total VHTs after link a is removed or disrupted and system traffic has been re-assigned to a new equilibrium, is found:

$$c_a = \sum_{i \in I/a} t_i^{(a)} x_i^{(a)}$$

Where $t_i^{(a)}$ is the new travel time across link i when link a has been removed or disrupted, and $x_i^{(a)}$ is the new flow on link i. Finally, the NRI of link a is calculated as the increase in total VHTs over the base case:

$$NRI_a = c_a - c$$

Therefore, the application of the NRI requires the specific definition of an analysis period for which an origin-destination demand matrix has been developed (Sullivan et al, 2009b).

It has been demonstrated that the Network Robustness Index (NRI) can be determined for a road network with isolating links by using a modified procedure which finds a capacity-disruption level other than 100% with which to run the procedure (Sullivan et al, 2009b). A procedure that utilizes capacity-disruption instead of link removal will be immune to the effects of isolating links in the network being studied. The modified procedure repeats the application across a range of capacity-disruption levels, usually between 30% and 99%. The rankings do not remain identical across all of the disruption levels, though. Therefore, it is important to find the capacity-disruption range where the ranking is the most stable and unchanging. To find the most stable level, the rank-orders for each consecutive disruption level are tested statistically to assess their correlation. The highest correlation between rank-orders is selected as the capacity-disruption level to use for that network/demand input (Sullivan et. al., 2010b). In this way, the modified procedure facilitates calculation of NRIs for real-world networks and allowed the modified procedure to be tested (Sullivan et. al., 2010a).

The Network Trip Robustness (NTR) is calculated by summing the NRI values associated with each individual link and dividing that sum by the total demand in the network:

$$NTR_n = \sum_{a \in I} NRI_a$$

$$\overline{\quad D_n \quad}$$

D_n is the total demand between all origins and all destinations in network n. D_n represents the total number of trips, so the units for the NTR are expressed as a unit of time per trip.

The total number of trips in the network is used in the denominator to normalize the individual NRI values as opposed to the total number of links in the network because the travel time and link flow calculations in the traffic assignment procedure are highly dependent on the number of links. In general, networks with fewer links tend to have higher travel costs than comparable networks with more links at the same level of demand.

The NTR is a measure of overall network robustness that is intended to compare networks with differing levels of connectivity and varying demand. It is important to note that although it provides a measure of network robustness, its use is not dependent on a specific type of disruptive scenario, nor does it address the probability a particular disruptive event might occur. In this study, the NTR is particularly useful in assessing the effect that the addition of a link has on overall network robustness.

3 Methodology and Results

3.1 Optimal Capacity-Disruption Level

The software tool developed previously was used to calculate NRIs for all network links at 69 link capacity-disruption levels between 30% and 99%. For the Chittenden County application, the highways geographic file from the Regional Transportation Model for forecast-year 2010 was used along with the origin-destination (O-D) travel matrix for forecast-year 2010. Intersection delays were not included in this application, and segmented links were eliminated from the road network, as in the pilot application (Sullivan et. al., 2010a).

Based on the conclusions of the pilot application of the NRI (Sullivan et. al., 2010a), only daily travel was modeled. Centroid connectors were not considered in the application. Daily travel was modeled by using a modification to the PM-peak O-D matrices for forecast year 2010. In order to simulate a full day of travel, the PM-peak O-D matrix was augmented by a factor of 10, at the advice of David Roberts, Senior Transportation Planner with the CCMPO. In addition, new linked-capacity fields were created to represent the daily capacities of the road network links. The new fields were created by dividing the hourly capacities by a k-factor. K-factors were taken from the statewide model where they were available (VHB, 2007), and estimated from similar roads if they were not. Since daily travel typically does not congest the network as much as peak hourly travel, this procedure provided an indication of the most critical links in the network from a relatively uncongested perspective, which is inclusive of all daily travel demands.

The benefit of testing every capacity disruption level between 30% and 99% was that the size of the “step” between levels could be evaluated. The modified NRI procedure stipulates that the stability of the rank orders from consecutive capacity-disruption levels be used to select the optimal level to use for our link ranking. The “step” between consecutive disruption levels may affect the optimal disruption level Therefore, in this application, step-sizes of 1%, 5%, and 10 % were tested to see if they would produce the same optimal capacity-disruption level. The Pearson product moment correlation-coefficient was used to assess the relationship between consecutive sets of NRI-based rankings. Figure 1 provides the results for each step-size.

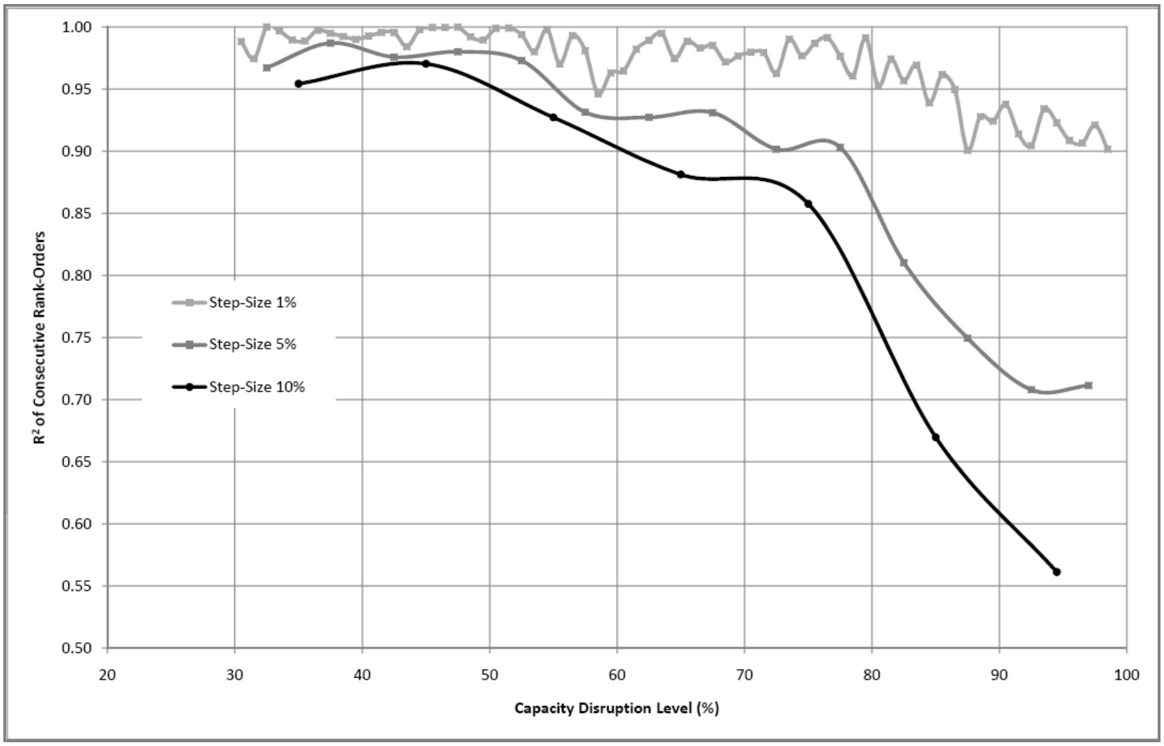

Figure 1 Pearson Product Moment Correlation Coefficients for each Step Size

In this application, the same 2010 road network was used, but new daily capacities have been created (as described above), and a link with an incorrectly-coded speed was re-coded (Sullivan et. al., 2010c). In any event, the rank-orders appear to stabilize at a similar point for all three step-sizes tested. The 1% step-size is most stable between 33% and 55%, reaching an R^2 value of 1.00 for 12 different steps in that range. The 5% step-size is most stable at 38%, and the 10% step-size reaches stability at 45%. Overall, these results agree fairly well with the findings of the pilot application, where 50% was selected (Sullivan et. al., 2010a). In fact, the difference between the rank-order at 33% and the rank-order at 45% is small (R^2 = 0.96). In this case, the result for largest step-size points to a broader region in the curve where the rank-orders are stable. Therefore, the 45% capacity disruption level was selected as the optimal, although it is likely that the results of this analysis will not change for any of the disruption levels between 33% and 55%. The most likely explanation for the difference in the capacity-disruption level selected here (45%) and the one selected in the pilot application (50%) is the introduction of more refined daily roadway capacities for this application.

3.2 Qualitative Identification of Potential Network-Representation Issues

Using the results of the NRI application, a visual investigation was performed to discern potential network-representation issues. For this investigation, road network links were re-drawn scaled by their respective NRI so that links with significantly high values could be easily identified. These network links were then overlaid on a GIS of all streets in the County, so that potential network-representation issues would be apparent. Examples of links with potentially significant omitted alternative routes are shown in Figures 2 with omitted routes represented by Old Stage Road, the northern extent of Woods Hollow Road, and Petty Brook Road / Sweeney Drive / Coon Hill Road. Each of these omitted routes presents a potential alternative route for a network link with a significant NRI. The road network was canvassed to identify similar locations.

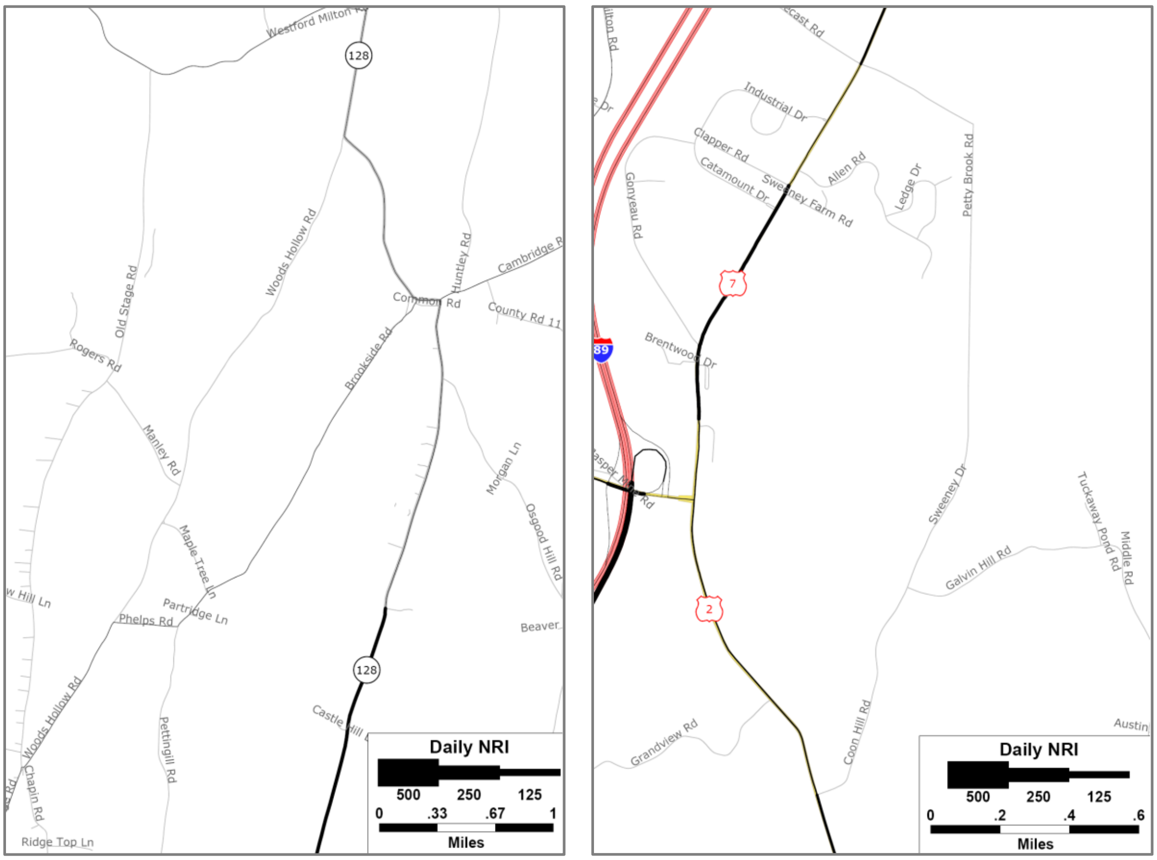

Figure 2 Examples of Potentially Significant Routes – Old Stage Rd, Woods Hollow Rd and Coon Hill Rd / Sweeney Dr / Petty Brook Rd

All of the potentially significant links identified are shown highlighted in red in Figure 3.

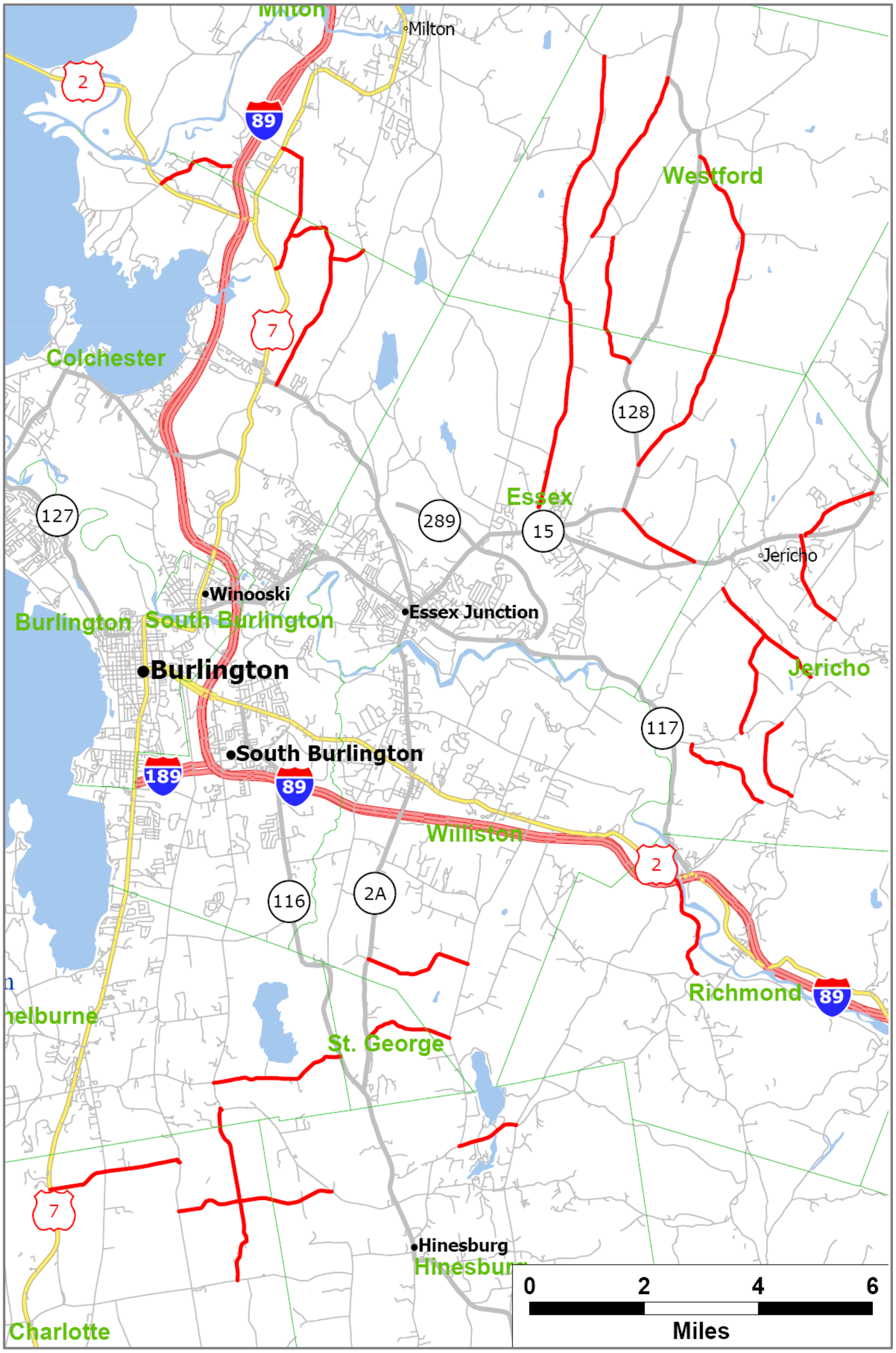

Figure 3 Potentially Significant Links

3.3 Quantitative Identification of Significant Omitted Links

Following this qualitative investigation, the NRI and the NTR were used to confirm which of these previously excluded links is significant to the road network and should be included in modeling exercises. Each of the links in Figure 3 was added to the road network individually and the modified NRI procedure was applied, and the NTR was calculated. The results of these applications are provided in Table 1.

Table 1 Quantitative Identification of Significant Omitted Links

ID	Town(s)	Potentially Significant Road Name(s)	NRI (hrs / day)[4]	NTR (hrs / day-trip)[1]	Change in NTR[2]	R^2 of Ranks[3]	Significant Link?
1	Milton / Colchester	Sweeney Dr / Petty Brook Rd / Coon Hill Rd	331	0.03	-81%	0.03	Yes
2	Milton / Colchester	Galvin Hill Rd / Middle Rd / Coon Hill Rd / Austin House Rd	1	-0.14	-201%	0.01	Yes
3	Milton / Colchester	Watkins Road	45	0.11	-19%	0.24	Yes
4	Westford	Old Stage Road[5]	44	0.01	-91%	0.06	Yes
5	Essex / Westford	Chapin Road	0	0.13	0%	1.00	No
6	Essex / Westford	Pettingill Road	0	0.14	4%	0.53	Yes
7	Essex / Westford	Osgood Hill Road	0	0.13	0%	1.00	No
8	Essex	Weed Road	0	0.27	100%	0.16	Yes
9	Westford	Woods Hollow Road	210	0.06	-56%	0.11	Yes
10	Jericho	Raceway Road	-17	0.01	-95%	0.02	Yes
11	Jericho	Packard Road	0.47	0.03	-74%	0.13	Yes
12	Jericho	Plains Road	0	0.13	0%	1.00	No
13	Jericho	Schillhammer/Plains Rd	0	0.13	0%	1.00	No
14	Jericho	Fitzsimonds Road[5]	0	0.13	0%	1.00	No
15	Jericho	Tarbox Road	0	0.13	0%	1.00	No
16	Richmond	Johnnie Brook Road	64	0.13	-5%	0.14	Yes
17	Hinesburg	Pond Brook Road[5]	1.7	0.24	76%	0.21	Yes
18	St. George	Ayer Road	0	0.13	0%	1.00	No
19	Williston	Butternut Road	0	0.13	0%	1.00	No
20	Shelburne	Pond Road	0	0.08	-43%	0.14	Yes
21	Charlotte	Lime Kiln Road	0	0.13	0%	1.00	No
22	Charlotte	Carpenter Road	0	0.13	0%	1.00	No
23	Charlotte	Dorset Street	0	0.13	0%	1.00	No

Notes:
1. NTR is the sum of all NRIs for the scenario divided by total demand, which was held constant.
2. Change in NTR is relative to the NTR of the base-case scenario, which does not include any of these links (0.13 hours / day-trip).
3. R^2 values compare the scenario NRI data with the NRI data for the base-case scenario.
4. If the scenario includes a set of links, this is the NRI of the link with the highest NRI.
5. Unpaved.

The results provide a definitive illustration that some of these links do in fact have an effect on the network flows. A change in the NTR was taken to indicate that the link affected network flows significantly. Therefore, these links are significant to the network representation and should be included in network models for the Chittenden County region. The Pearson product moment correlation coefficients were also calculated between the link rankings which resulted from the scenario application and the base-case link rankings, as ranked by the NRIs. These results confirmed that the rankings matched well in every case where the NTR was found to have not changed. It may be necessary to use both calculations, however, since the addition of the omitted link did not improve the network's ability to handle user-equilibrium flows in every case. For Pettingill Rd, Weed Rd, and Pond Brook Rd, the consideration of the omitted link diminished the robustness of the network, indicating the presence of Braess' Paradox (Sullivan et. al., 2009b). However, these links are still considered to have a significant effect on the network flows and should be included.

The results also indicate that the NRI alone is not an adequate indicator of the significance of given link when inter-network comparisons are being made. This finding attests to the need for the NTR as a defining network characteristic for evaluations such as these (Sullivan et. al., 2009a). The finding that adding a link to the network can increase the NTR even when the NRI of the added link is 0 is counter-intuitive, but is certainly a practical result of this analysis. Since the NRI is dependent on the business-as-usual equilibrium flow state for each scenario and the addition of a link to the network changes that equilibrium flow, there will not be a direct relationship between the NRI of any link and the NTR of the network.

4 Conclusions

The focus of this study was the tendency for minor and local roads to provide significant robustness gains as they offer critical alternative routes during disruption events. The overall conclusion of this report is that the application of the NRI and the NTR can be used to identify these links, and test their significance. By examining the change in NTR that occurs when a previously omitted link is added to the network reveals its significance. In this study, a set of 23 links were identified qualitatively in Chittenden County which are currently not included in the region's transportation model but may be significant. These 23 links were tested qualitatively and a total of 12 were found to be significant. Based on these findings, future applications of the regional model (CCMPO, 2008) should consider the influence of these links to overall network dynamics. If possible, these links should be included in the network representation for all analyses going forward.

The results of this study also have general implications for travel demand models which are increasingly being used to help decision makers with a wide range of critical policy questions. Sophisticated models exist only for large urban areas, and often these models do not include secondary roads required to study relevant policy issues such as robustness and resiliency. Statewide models are often characterized by the use of very large TAZs which can preclude effective evaluation of detailed road networks. The aggregation of links in a transportation network can have some unintended consequences. This study suggests it is timely to investigate ways of generating model networks that consider the full functional connectivity of the highway system. In recent years, transportation-related policy questions have increasingly shifted away from focusing only on congestion to focusing on a much broader and complex range of questions that require integrated travel and land use modeling. For example, tailpipe emissions modeling for GHG program development may soon be required in all areas – not just urban areas. Consideration of biking and walking requires analysis of all roads not just major roads. The aging population has created a large future demand for rural public transit or demand responsive transit. These policy questions will require expanding the framework of travel demand forecasting models to include more roads, potentially complete networks.

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