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Travel Importance and Strategic Investment in Vermont's Transportation Assets

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Executive Summary

In recent decades, the “wear-and-tear” of the last 60 years of travel on our nation’s transportation infrastructure has outpaced our ability to maintain our highways. In an environment of scarce public resources, addressing this problem will require a re-thinking of our current approaches to strategic transportation planning. As networks become increasingly saturated, focus on the most highly-traveled elements is not enough. New performance measures are required to provide objective information for identifying critical elements in saturated networks under disrupted flow regimes to ensure that scarce resources can be utilized effectively.

This project advances a new type of system-wide measurement of link criticality that will provide the tools needed for strategic disinvestment in roads that are not critical to the health and welfare of Vermonters. This new approach requires a paradigm shift in our current planning function and in the methods used to measure the importance of transportation system components. In this research, the Network Robustness Index (NRI) methodology is modified to include a process for considering the reason for travel in valuing roadways in Vermont. In addition, a new planning metric based on critical accessibility to emergency services is introduced, and combined with the NRI to yield a new measure, the access-based NRI (aNRI), that is uniquely suited to disinvestment planning.

Based on the statistical evidence presented in this report, the exact method used in valuing travel purposes for the calculation of the modified NRI (mNRI) is critical to the calculation of the least critical links in the roadway network. The statistical test used demonstrated evidence of differences in the rank orders at the bottom of the lists generated by each method. The bottom of the rank orders are presumably the links that are most useful for decision-makers considering disinvestment scenarios, so this finding is very important.

All of the ranking methods tested in this study produced more defensible rank ordering of the most and least important links in the network than simply assuming that all trips are equivalent in terms of importance. Using the original NRI method, most of the links in the analysis revealed an equal level of importance with an NRI of 0, providing no discernible change in total travel time on the network when disrupted. However, using the methods that included alternate approaches to valuing trips on the network created rank orders without ties, making the overall list more useful for prioritization of links for strategic investment.

Method 2a of the mNRI produced a set of links at the top and bottom of the rank-ordered lists that was more uniformly dispersed throughout the state, and its valuation method is consistent with methods used in other analyses conducted by VTrans which focused on strategic investment (Sullivan, 2013).

Non-critical links in the state, which might be targets for strategic disinvestment, consist primarily of smaller segments of roadway dispersed fairly evenly throughout the state. Some non-critical links are in areas that are particularly rural and not highly travelled, but others are in more urbanized areas, where excessive redundancies might be present. The bottom 12 least critical links in the state are shown in Table A in order of increasing criticality.

Table A Bottom 12 Least Critical Links in the State for the mNRI, Method 2a

Road Name	Primary Town	Length (mi.)	Hourly Capacity (vphpl)	Speed Limit (mph)	2010 AADT (vpd)
Colchester Avenue	Burlington	0.20	700	30	11,100
Shelburne Road / US Hwy 7*	Shelburne	0.48	800	40	14,360
North Main St / US Hwy 2	Waterbury	0.00	1,575	40	6,340
US Highway 7	Charlotte	2.19	800	50	10,990
Roosevelt Hwy / US Hwy 2	Bolton	2.92	500	50	2,660
Spear Street	S. Burlington	0.78	700	30	4,900
Ramp to I-89S from 100N	Waterbury	0.19	1,600	30	NA
Upper Main St / State Rte 15	Essex	0.09	800	45	15,250
Ramp from I-89S to Great Brook Rd	Middlesex	0.24	1,600	30	NA
Roosevelt Hwy / US Hwy 2*	Milton	0.89	800	50	9,210
Schoolhouse Road*	Dummerston	2.02	950	30	NA
Spear Street	S. Burlington	0.44	700	30	4,900

Notes:

*** -** denotes a roadway which traverses one or more bridges

NA – AADT not available for 2010

In all, 11 separate towns are represented in the list, further reinforcing that the method does not focus solely on one region of the state, nor does it focus solely on urbanized areas. In addition, the variation of travel on the roadways, as represented by AADTs on these links, reinforces the non-intuitive nature of this metric, with its focus on redundancy and the value of various trip purposes. The lower hourly capacities of these roadways is notable, however, as the tendency for relatively high levels of travel on low-capacity links with a high-capacity redundancy often represents a target for strategic disinvestment.

As noted previously, the least critical links are inherently shorter segments of roadway than the most critical links, indicating that they exist in areas with better roadway connectivity than the most critical links. Also noted in the table are the roadways traversing one or more bridges. These roadways are identified because bridges have an inherently greater cost of maintenance and repair than typical roadway segments, so these links might be particularly strong candidates for strategic disinvestment.

Of final note in the list of the least critical links in the state are two interstate ramps, an entrance ramp and an exit ramp. Most interstate interchanges in the state have a complete set of four ramps to access both directions of travel on the interstate, entering and leaving for each. This analysis demonstrates that, in fact, one of these access ramps is often much less useful than the others. However, it may be the case that leaving one of the ramps off the interchange was not an option when it was constructed. The evolving nature of travel on our interstates may indicate that interstate ramps are a good target for strategic disinvestment.

The appeal of strategically disinvesting in links that do not exhibit significant importance to the Vermont economy is an ongoing motivation for the rank ordering, and the reason why including access to emergency services was determined to be necessary. The research team working in this field wanted to avoid the possibility of recommending a link for disinvestment when it was, in fact, serving the important purpose of providing access to emergency services.

An increasing focus of policies which consider strategic disinvestment is the presence of bridges on low-value network links. Bridges comprise a much larger investment in a state's infrastructure than land-based roadways. Therefore, a roadway with a bridge represents a greater opportunity for strategic disinvestment policy than one without a bridge.

With these considerations in mind, the roadways at the bottom of the rank order measured by the aNRI which utilize one or more bridges is provided in Table B.

Table B Least Critical Links in Vermont with One or More Bridges by aNRI

Road Name	Town	Link Length (mi.)	Capacity (vph)	Speed Limit (mph)	2010 AADT	No. of Bridges	aNRI
North Ave. / State Rte 127N Entrance / Exit	Burlington	0.21	900	40	NA	1	-0.72
I 91 North	Brattleboro	0.46	3,600	55	NA	1	0.00
US Hwy 4	Fair Haven	1.78	3,520	65	3,360	1	0.00
N. Goddard Hill Rd.	Westminstr	7.02	1,050	40	760	1	0.00
I 89 South	Swanton	0.30	4,000	65	NA	1	0.00
I 89 South	Highgate	6.20	4,000	65	2,025	1	0.00
Lake Rd. / State Rte 120	Franklin	4.44	1,050	40	910	1	0.00
I 93 North	Waterford	7.27	4,000	65	2,765	3	0.00
State Rte 102	Brunswick	5.24	1,050	40	480	2	0.00
State Rte 102	Bloomfield	3.64	1,050	40	330	1	0.00
US Hwy 7	Highgate	0.37	1,050	40	370	1	0.00
Ethan Allen Hwy / US Hwy 7	Highgate	2.83	1,050	40	540	2	0.00
Berry Hill Rd.	Sheffield	6.21	950	30	NA	2	0.00
I 91 North	Barton	0.37	4,000	65	NA	1	0.00
I 91 South	Weathersfld	0.26	4,000	65	NA	1	0.00
I 91 South	Bradford	0.38	4,000	65	NA	1	0.00
I 91 North	Barnet	0.44	4,000	65	NA	1	0.00
Carter Hill Rd.	Highgate	3.47	1,050	40	670	1	0.00
Valley Rd.	Holland	6.31	950	30	NA	1	0.00
Broad Brook Rd.	Royalton	8.92	950	30	NA	4	0.00
I 89 North	Williamstwn	0.25	4,000	65	NA	1	0.00
Kelley Stand Rd.	Sunderland	13.98	1,050	30	90	6	0.00
Victory Rd.	Victory	7.67	1,050	40	NA	1	0.00
Rupert Rd. / State Rte 153	Rupert	2.94	950	30	NA	1	0.00

The notion of variable trip importance is controversial, since it creates a distinction in the network between trips that are going to be valued highly, and those that are not. The controversy comes when it has to be determined which trips are to be considered more essential to the system. Trips made by emergency vehicles are already implicitly given preference over other types of trips through the use of lights, sirens and, in some cases, traffic signal control. Should critical freight trips be included as well? What about commuting traffic? Should the value of time vary for different users?

There may be significant resistance to promoting the protection of one type of travel over another, when the road network has traditionally been equally accessible for all trips. Politically-charged examples of this controversy exist in the literature and are becoming more prevalent with the proliferation of congestion pricing, which is itself a form of trip purpose valuation.

1 Introduction

In recent decades, the "wear-and-tear" of the last 60 years of travel on our nation's transportation infrastructure has outpaced our ability to maintain our highways (FHWA, 2008).The I-35W bridge collapse in Minneapolis in August 2007 brought the poor state of the nation's roads and bridges into the national spotlight and the closure of the Crown Point Bridge in October 2009 brought it into the local consciousness here in Vermont. Consequently, more members of the public, the research community, and the regulatory community are willing to consider a shift in the way our transportation systems are managed.

In an environment of scarce public resources, addressing this problem will require a re-thinking of our current approaches to strategic transportation planning. Infrastructure planners typically focus resources on links in a network that have the largest volume of flow passing through them, optimizing the "business as usual" flow regime. For road networks, the metric used to measure a link's importance is often the average annual daily traffic (AADT), collected from traffic counters, or the volume-to-capacity ratio (v/c), a common output of travel-demand models (FHWA, 2008). A shortcoming of both the AADT and v/c ratio is that they provide only localized static information. Neither measure considers system-wide impacts or impacts resulting from the rerouting of traffic after a network disruption.

As networks become increasingly saturated, though, focus on the most highly-traveled elements is not enough. New performance measures are required to provide objective information for identifying critical elements in saturated networks under disrupted flow regimes to ensure that scarce resources can be utilized effectively. These measures need to consider the relative value of each link to the entire network – going beyond localized measures based on flow volume in a single system-state. Alternative functioning states must be considered if the system is to function optimally in the face of the types of disruptions that have become common (e.g., road closures, bridge collapses, and degraded pavements). Including the network-wide effects of these disruptive states in a performance measure will also make decisions more equitable, since a wider variety of flow regimes (and users) is considered.

With the advent of the economic recession in the United States in 2008 and the subsequent passage of the American Recovery and Reinvestment Act (ARRA), attention has focused on a "fix-it first" policy, which in some regions has vilified the addition of new capacity to our networks (NJDOT, 2009). In addition, vehicle-miles traveled (VMT) on the nation's highway network plateaued around 2004, and even declined in 2008 for the first time in nearly 30 years (Brookings, 2008). Transportation professionals are responding to financial constraints and diminished use with a new focus on preservation. The need to be wise with scarce transportation funds has caused the industry to become more thoughtful about where its investments are spent.

This project advances a new type of system-wide measurement of link criticality that will provide the tools needed for strategic disinvestment in roads that are not critical to the health and welfare of Vermonters. This new approach requires a paradigm shift in our current planning function and in the methods used to measure the importance of transportation system components. In this research, the Network Robustness Index (NRI) methodology (Scott et. al., 2006) is refined to include a process for considering the reason for travel in valuing roadways in

Vermont. Three new approaches to valuing the reason for travel are tested and the results are compared to one another. In addition, a new planning metric based critical accessibility to emergency services is introduced, and combined with the NRI to yield a new measure that is uniquely suited to disinvestment planning.

1.1 Strategic Network Planning Metrics

Over the past decade, transportation network studies that focus on disruption scenarios have increased to account for security-related policy questions. We define *network robustness* as the degree to which the transportation network can function in the face of some type of capacity disruption on component links. A robust network adapts or adjusts to disruptions in the network much more easily than a non-robust network. Conversely, *network vulnerability* is the degree to which a transportation network ceases to function effectively when one or more links are disrupted. The vulnerability of a transportation network is of particular concern given its importance to personal mobility, supply chain management, security, energy, and food distribution. So it is becoming increasingly clear that disruption simulations must be considered in decisions to allocate resources to maintain and improve our transportation systems.

Network planning can be approached operationally or strategically for transport networks (Ukkusuri et. al., 2007). Operational network-planning would require new control systems which rely on widespread behavioral cooperation amongst network users, unlikely on an open public network like the highway system. As such, operational planning is more typically implemented at the project-level, for specific intersections or links. One exception is the specific consideration of freight-commodities, whose routing can be controlled externally, isolated from other travel on the public road system. The field of freight-commodity transport, which can be considered a subset of all operational network-planning approaches, has been thoroughly investigated in operations research and management science (Muriel and Simchi-Levi, 2003; Powell, 2003). For these reasons, operational network-planning is not explored in this project.

Strategic network-planning might target improvements and strategic disinvestments in a network by simulating additions or deletions of network elements. Strategic planning efforts often need to consider ALL travel in the network, to advocate for network elements that are more important to the public good. Inter- and intra-network indices are commonly used to implement this type of approach. To compare separate networks, or distinct sub-networks (inter-network comparisons), it is necessary to measure the performance of the network. These types of measures can be useful when large-scale budgeting decisions need to be made amongst a number of separate networks within, for example, a state, or when budgeting decisions need to be made amongst several options for the future of an urban network. However, to quantify the relative contributions of individual links and/or nodes to network performance, intra-network comparisons are made. The overall goal of intra-network comparisons is to identify the most critical links in the network to fortify, augment, or protect and the least critical links to disinvest in. One of the more common ways of providing output for intra-network comparisons is to provide a ranking of the network links or nodes based on their relative contribution to the robustness of the network.

Measures which can be used for inter-network comparisons are not common in the research literature, particularly when the complexities of physical infrastructure networks are considered. Static descriptive measures are often considered indicators of performance in network science. These types of measures include alpha index, gamma index, network density (Rodrigue et al, 2009), assortative-mixing coefficient (Gupta et al, 1989), degree distribution, clustering coefficient, and mean shortest-path distance (Newman, 2003). However, none of these measures considers flow in the network in its evaluation of performance. The Network Trip Robustness (NTR) is a performance measure that is calculated from the NRIs for the network (Sullivan et al, 2010). It provides information about the robustness of the entire network to a variety of disruption scenarios. There are currently few other attempts to develop a scalable measure of network-wide robustness for the purpose of comparing networks.

1.2 Motivation

Most methods of measuring a link's relationship to the entire network relate a single link to the overall network connectivity and structure. Examples of these measures are degree (Newman, 2003), clustering (Watts and Strogatz, 1998), shortest-path distance (Newman, 2003), assortativity (Newman, 2003), and between-ness centrality (Freeman, 1977). Only the NRI (Scott et al., 2006; Sullivan et al, 2010) uses a simulation procedure that includes consideration of not only the "business as usual" flow on a given link, but the potential traffic that might use the link if conditions in the network changed. Few or none of these established strategic-planning measures include consideration of the individual importance of trips, paths or destinations. In order to make our transport networks more efficient, robust and effective, we need to begin considering the importance of specific trips on the network. Until now, all travelers have had an equal right to the network. Giving precedence to travel that is more important to the public good is a necessary next step in our desire to achieve greater value for our transportation investment.

Enforcing variable importance on a network is not without precedent. Service vehicles, with alarms, sirens and flashing lights, enforce an informal precedence, when they respond to an emergency. Many telecommunications networks already work with precedence rules, and other physical infrastructure networks are exploring similar types of rules governing flow, in order to reduce congestion and increase efficiency. Methods for scheduling the transmission of data packets according to prioritization schemes are expected to reduce costly delays in information-transmission (Yaghmaee and Adjeroh, 2009). Transit-signal priority (TSP), used extensively in other parts of the world, is becoming more common in the United States. TSP consists of a detection system for identifying transit vehicles approaching an intersection and software which implements priority control strategies to facilitate preferential movement of transit vehicles through a signalized intersection (Smith and Hemily, 2005). The implication of TSP systems is that travel by transit vehicle is more important than travel by other modes. Simplified TSP systems are currently being implemented by the Chittenden County Transit Authority in Vermont.

Studies of stated-preference of transportation-network users provide further support for priority enforcement in travel (NCHRP, 1999; Weisbrod et al., 2003). Many of these studies indicate that users value travel differently by trip purpose (e.g., work vs. non-work), and feel that more important trips should have preference (Mackie et. al., 2003). Congestion problems are expected to improve with increased flow efficiencies resulting from a more priority-based ranking for link improvement. Therefore, the next generation of performance measures for links and networks must account for the relative importance of flow.

In this project, we incorporate the reason for a trip and the value of different trip purposes into the existing NRI methodology. Including trip values in the modeling approach allows decision-makers to examine the impacts of travel-time delays on both discretionary and non-discretionary passenger trips independently on an entire network. In addition, consideration is given to how delays to freight may affect the network. The types of decisions that are affected include prioritization of maintenance and improvement projects, influencing of route-choices and emergency-service routes, and the need for development of communications infrastructure.

Two separate methods of a new importance-based NRI methodology are tested to determine how they affect the ranking of links in the state's roadway network. Each of the rankings that results from the two methods, including three separate applications of the second method, are compared to one another, and to the ranking that results from the original NRI methodology. In addition to this comparison, an in-depth analysis of the links that fall in the bottom of the ranking is conducted, with recommendations for links to consider for disinvestment.

2 Research Related to Travel Importance

This section includes a review and categorization of recent research exploring the importance of traffic flow and approaches to incorporating importance into existing link-based performance measures. There are two fundamental *approaches* to classifying travel to understand how its importance can be used in transportation planning. The first classification considers travel as a way of accessing things we want and need, by moving goods and people between origins and destinations. In this sense, travel is only as valuable as the access it provides, which can be measured by the travel time needed to reach certain destinations. The second classification regards all travel as a disutility, something travelers seek to minimize to the extent possible while serving their basic needs. The second classification is effectively hedonistic, assuming that the maximization of leisure time is the ultimate goal of all travelers.

Within these classifications, there are two general *methods* of applying value to travel. The first method is based on the actual path used to travel, and the travel time incurred by the use of a specific set of links. The second method is access-based, making specific use of the relative locations of selected destinations to assess the value of each link in the roadway network. Both methods are discussed in detail below.

2.1 Path-Based Methods

Path-based importance has been discussed in the transportation literature for decades, but has not been used extensively for increasing the effectiveness of strategic network-planning. Path-based importance measures in the transportation literature include measures based on:

1. Value of time
2. Value of purpose
3. Combined (value of time by purpose)

Path-based measures of travel importance are discussed in further detail in the following subsections.

2.1.1 Value of Time

In the research literature, the value of time has been expressed as a quantitative monetary variable. The value-of-time (VOT) (Rouwendal, 2003), the Subjective Value of Time (SVOT) (Armstrong et al., 2001), and the Social Price of Time (SPOT) (Mackie et al., 2001) are some examples of variables used by researchers. Roadway users represent a diverse mix of travelers with different trip purposes travelling at different times of the day. As such, transport economists recognize that when evaluating the predicted benefits of congestion-mitigation actions, different user values of time must be taken into account.

The research literature dealing with travel time introduces additional variables specifically related to travel - the Subjective Value of Travel Time (Mackie et al., 2001) and the Value of Travel Time Savings (VTTS) (Gunn, 2001). These variables are similar, given that all are used for assigning a monetary value to a single time unit. De Serpa (1971) identified three conceptions of time value – as a resource, as part of an activity, and as a separate activity that is minimized for certain constrained activities. Each of these conceptions monetized time in a different way. The first deals with the monetary value of an increase in available time. The second deals with the ratio between the marginal utility of an activity and the marginal utility of money. The third deals with the monetary value, as a willingness to pay, of a reduction in the constrained time assigned to an activity.

The utility of time is often considered when a measure of its value is being investigated. Rather than regarding the value of time spent on an activity directly, some researchers assume that there is an implicit time that one desires to spend on the activity. These implicit times can be positive, whereby time spent increases the user's overall utility, or negative, whereby time spent on the activity decreases the user's overall utility. The value of travel time, then, can be related to the extent to which it affords additional leisure and, therefore, happiness. Jara-Diaz et. al. (2008) assign every unpleasant activity other than work an exogenous minimum utility, so that "the sign of its marginal utility is the same irrespective of duration under this specification. This does not mean that an activity that is assigned the minimum time is necessarily unpleasant, because the optimal time assignment could be less than the exogenous minimum." This approach pre-supposes a desirability of activities with, for example, work behind leisure.

These approaches are readily translatable to the importance of individual links, which is a necessary step to reaching a ranking that will be useful to traffic operations personnel. These methods value a trip based on its travel time, with the cost created by the operator's or passenger's time spent traveling, and the time spent transporting freight.

Two types of travel are considered when the value of time for travel is determined. The first type is the productivity of travel undertaken in the context of a remunerated economic activity (e.g. work and/or freight travel) and travel undertaken in the context of un-remunerated "personal" travel. Travel for a remunerated economic activity is easier to place a value on, since salaries and prices are already set for travelers and the commodities they transport. Emergency and medical transportation is also of great concern for its effect on overall human well-being. One study only distinguishes between emergency/medical trips and other trips for the purpose of assessing the impact of a planned bridge closure (WSDOT, 2003).

Some studies have used stated-preference surveys to identify the variations in user's valuation of travel time (NCHRP, 1999). Many of these studies find a strong relationship between the user's level of income and their stated value of travel time. Those with higher incomes tend to value their travel time more highly. For this reason, travel-time costs are often expressed as a fraction of the user's wage rate (VTPI, 2010). Another important finding is that this valuation depends strongly on whether the travel is under congested conditions. Delay times and waiting times in travel tend to be valued more highly than free-flow travel time, and travel time for work tends to be valued more highly than personal travel. The average value of travel time for average trip length (15 miles; 26 minutes) and median household income ($50,000 per year) was estimated to be $5.30/hour (NCHRP, 1999). However, the average value of reliability for the average trip length and median household income ($55,000 per year) was $12.60/hour of standard deviation in the data set (NCHRP, 1999).

The impact of reduced travel-time reliability is felt primarily through its impacts on road users' travel time budgets. These budgets are largely conditioned by scheduling constraints imposed by daily activities. While this may be less true for leisure-related trips where scheduling constraints may be weaker, it holds for commuting trips (conditioned by the work day) and freight/business travel (conditioned by work constraints and delivery windows). The costs of travel time for freight are compounded by the value of the commodity being transported and the value of the vehicle being used for transport, both of which are added to the value of the driver's time. The value of the freight commodity can include the value of the shipment, and the inventory-holding costs imposed on the supply chain by the time spent in transit. Congestion affects businesses not only through the direct impacts of additional fuel, labor and vehicle running costs, but also through downstream impacts on logistics chains. These impacts can reduce the overall benefits that businesses derive from locating in large urban markets. This compounding makes the value of time for freight transport considerably higher than any of the other categories of individual travel considered, with $/hour costs of around $25, and reliability costs in the hundreds of dollars (NCHRP, 1999; Weisbrod et al, 2003). Even high income travelers do not value their individual travel time nearly as much (those earning over $95,000 per year average about $8 per hour) (NCHRP, 1999).

Importance has a natural fit in supply-chain studies, where commodities are typically being moved through a public network, and the commodities by nature have varying values depending on exactly what the commodity is and whether or not there are time-based constraints on usage (such as perishable products), and therefore varying importance. One distinction in this case from the more general inventory-holding problem is that we are concerned with importance to the general public and enforcing precedence in a public network. Supply-chain studies typically assign importance from the shippers' perspective in an effort to minimize their individual costs. This viewpoint puts the shipper at odds with other users of the network, including other shippers and the general public on the nation's highways because there is no consideration given to other network users.

While "just-in-time" supply strategy is often used synonymously with "fast" or "speedy" delivery, the real value of this type of logistics process is that goods are delivered at the "right time" – that is, precisely when they are needed. This is an important distinction to make with regards to congestion impacts on firms operating "just-in-time" production lines. Travel times that are predictably slow can be accounted for with adequate buffer periods. However, unplanned delays, such as those engendered by unreliable travel conditions, have a significant impact on "just-in-time" processes and cause firms to increase costly inventory holdings. This is especially true for sectors characterized by a large percentage of perishable, expensive or difficult to store goods (e.g. refrigerated foods, high value electronics and seasonal apparel).

Agricultural transportation is an example of travel with a rigid delay constraint, since its commodities are susceptible to spoilage. This type of transportation requires consideration of the total value of the shipment, since the entire value can be lost by a travel delay. Another example is ambulance travel. Ambulances cannot be delayed in the same manner as leisure trips. However, ambulance travel is accommodated through the use of sirens and flashing lights, which are universally recognized as yield signals to other vehicles. Other less critical examples of travel with rigid delay constraints are those of inventory-routing for systems that utilize vendor-managed inventory to prevent customers from running out of inventory (Cordeau et. al., 2007). Trips with rigid delay constraints such as these might have a delay-cost curve as shown in Figure 1.

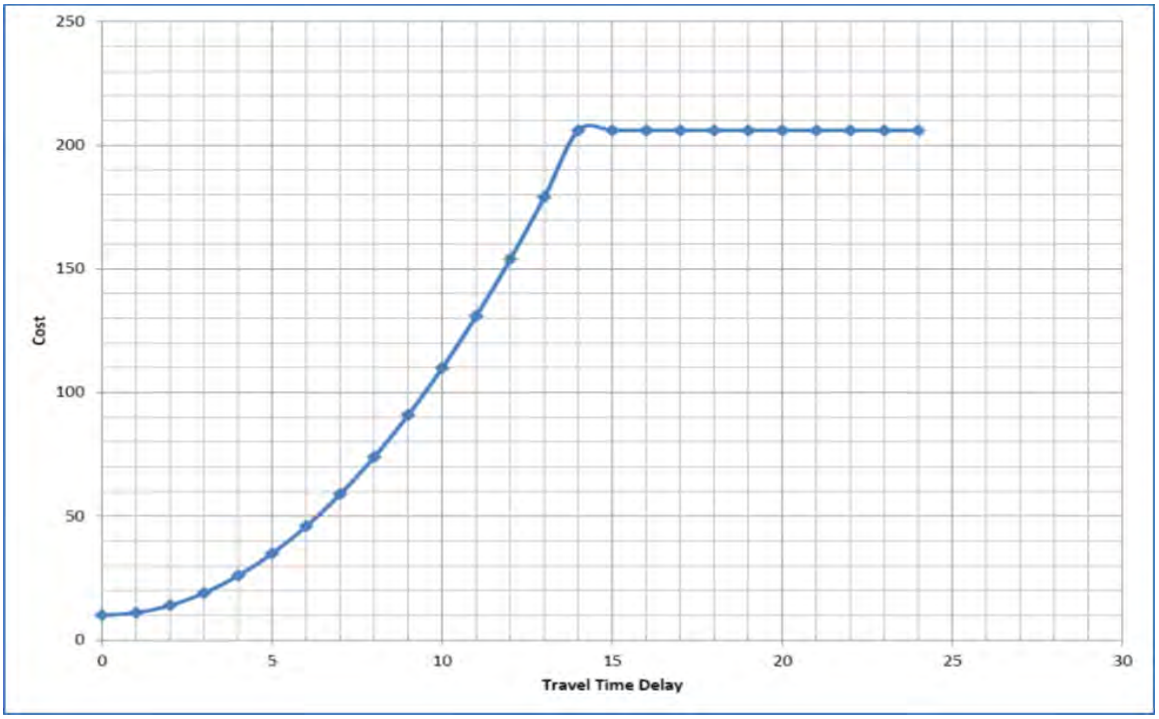

Figure 1 Example of a Delay-Cost Curve with Rigid Delay Constraints

Note from the figure that costs are present for the free-flow trip initially due to the monetary cost of travel time, but they increase exponentially as the users expected travel time is delayed. This type of delay-cost relationship is common for airline travelers (Wu and Caves, 2000). For trips with rigid delay constraints, though, these costs reach a maximum when a threshold is reached (14 minutes in Figure 1), and the full cost of the delay has been incurred; for example, a meeting has been missed or a perishable product has spoiled.

2.1.2 Value of Purpose

An example of a method for identifying the importance of links based on the value-of-purpose is the traditional classification of roadways by the Federal Highway Administration (FHWA, 1989). Roads were functionally classified by FHWA as arterials, collectors and locals. Most state classification criteria were based primarily on roadway capacity, traffic volume and operational characteristics. However, FHWA recognized the trip purpose as the basis of classification. Under FHWA guidelines, roads were defined based on criteria recognizing the following 12 trip purposes:

1. Travel to and through urbanized areas
2. Travel to and through small urbanized areas

3. National defense

4. Interstate and regional commerce

5. Access to airports, seaports, and major rail terminals or intermodal transfer facilities

6. Access to major public facilities

7. Interconnection of major thoroughfares

8. Access to minor public facilities

9. Interconnection of minor thoroughfares

10. Access to concentrated land uses

11. Access to diffuse land use areas

12. Travel between home, work, entertainment, and shopping destinations and the nearest road on the primary road network composed of arterial and collector roads.

Roads serving at least two of the purposes numbered 1 through 7 were classified as Principal Arterials. Roads serving only one of the purposes numbered 1 through 7 were classified as Minor Arterials. Those serving the purposes numbered 8 through 11 were classified as collectors, and those serving purpose 12 were classified as local streets.

Today, the following trip purposes are common in the literature with respect to importance (ECMT, 2007; WSDOT, 2003):

- Commuting
- School transport
- Professional/business
- Personal/social
- Tourism
- Freight
- Medical/hospital

Often these purposes are further categorized for the purpose of ranking. For example, work trips are often distinguished as those made to or from work (commuting) and those made for work (including freight and professional/business). Travel for work is generally assigned a higher value than commuting travel, the latter still being regarded as occurring under the user's personal control. All types of travel that are constrained by stronger scheduling restriction, like school transport, commuting, freight, and professional/business are normally regarded as more important than those that have weaker constraints, like tourism and personal/social.

An additional distinction is common between discretionary travel and non-discretionary travel, based on the perceived need for the trip. Non-discretionary travel is normally regarded as more important, but it can include some aspects of personally-controlled travel, like grocery shopping or school.

Another trip-categorization framework provides a more behavioral description of household travel and brings about a more detailed distinction between work and non-work travel (Reichman, 1976). This scheme contains three major classes of travel-related activities:

- Subsistence activities, to which members of the households supply their work and business services; travel associated with this activity is most commonly commuting;
- Maintenance activities, consisting of the purchase and consumption of convenience goods or personal services needed by the individual or household;
- Leisure or discretionary activities, comprising multiple voluntary activities performed on free time, not allocated to work or maintenance activities

Using this classification scheme, activities for work, school or college trips are considered subsistence. Maintenance activities include personal, appointment, and shopping. Discretionary activities would be visiting and free-time. A more recent study deals with the presence of multiple trip purposes within a single trip-chain or tour (Krizek, 2003).

In some contexts, a more restrictive constraint on access is appropriate for consideration of trip importance. "Critical" access is a purpose-based method of assigning value to trips by access, but with a binary distinction between "critical" and "non-critical" trips. "Critical" trips are given equal value, with preference over all "non-critical" trips. This approach to valuation of trips is appropriate for ensuring access for police, fire, medical, or hospital-related travel. "Critical" travel is generally a category of trips that is essential to human health and welfare.

2.1.3 Combined Methods

Other approaches have used a combination of these methods for assigning value to trips (Husdal, 2005). For example, a distinction between the VTTS of three trip purposes is explored by Zamparini and Reggiani (2007). The findings of this study are consistent with previous findings – trips for "employer's business", which include trips for work, like freight trips or trips to/from business meetings, are valued more than twice as highly as commuting trips. Another study analyzes the hourly value of time for "on-the-job" and "off-the-job" trips, finding "on-the-job" trips to be approximately twice as valuable (ODOT, 2004).

A study of equitable re-routing of air traffic during airport congestion includes consideration of the specific airline involved in the flight, noting that all airlines have to be treated fairly when re-routing is considered. This method is a form of valuation based on delay with the airline affected by the delay as a proxy for trip-purpose, although it seeks only fairness, not efficiency (Bertsimas and Patterson, 2000).

2.2 Access-Based Methods

Destination-based importance is not explored independently in the literature with respect to network planning. This omission is probably due to the fact that origin or destination importance is often felt to be easily derived from trip importance and is closely related to value-of-purpose. However, in a subset of cases, the importance of the destination node in the network is independent of the trip purpose or length, and trips destined for the node in question are more difficult to isolate. In such cases, it is often more effective to focus on a generalized measure of accessibility to/from these destinations.

Accessibility metrics can be classified in two ways, depending on whether access is being measured as a distribution of destinations, or the costs incurred by a certain group of people. In addition, these metrics are used in two different ways. First, they are used to measure the accessibility available for a group of people, typically from empirical data. Second, they are used to prescribe a normative standard for accessibility from theoretical data, particularly with respect to acceptable travel times. Paez et. al. (2012) refer to these classifications as *positive* and *normative* approaches, respectively.

3 Formulation of Importance Metrics

Two new methods of incorporating importance into transportation planning are presented in this section. These methods build upon the existing method of calculating the NRI, which assumes all travel is equally important (Sullivan et. al., 2010). This method is referred to as Method 1. The path-based formulation is referred to as Method 2, and results in a new formulation of the NRI, denoted as mNRI or modified NRI. The access-based formulation is referred to as Method 3, and results in the Critical Accessibility (CA). A Combined Method is also described which is comprised of Method 3, and either Methods 1 or 2, resulting in a new measure of link importance, the Access-Based Network Robustness Index (aNRI).

3.1 Method 2: A Path-Based Formulation

Network routing problems typically translate node-specific travel-demand, or travel requirements, into estimates of the link-specific flows that will result, assuming that the links constituting each path are known:

$$x_a = \sum_r \sum_s \sum_k f_k^{rs} \, \partial_{a,k}^{rs} \qquad (1)$$

This equation states that the flow *x* on each link *a* is the sum of the flows for all paths *k* connecting origin node *r* and destination node *s* using that link. For all links in the network *A*, $\partial_{a,k}^{rs} = 1$ if link a is a part of path *k*, and $\partial_{a,k}^{rs} = 0$ otherwise (Sheffi, 1984). Of course, path *k* is not the only option for all travel (*q*) from *r* to *s*:

$$\sum_k f_k^{rs} = q_{rs} \qquad (2)$$

In the transportation field, network routing has been widely explored since the 1950s, and commonly used routing algorithms have been shown to correlate well with user-behavior in a travel environment with a wide variety of choices. Network-flow regimes estimate link-specific flows for one of two goals for travel required on the network – user-specific optimality or system-wide optimality. User-specific optimality constrains network flow to minimize costs for each individual user, but system-wide optimality constrains flow so that network-wide costs are minimized. In certain circumstances, if the cost function is link-separable and monomial, user and system-wide optimal flows coincide (Marcotte and Patriksson, 2007). In complex transport networks, however, the two flow regimes are almost never identical. The primary reason for this incongruity is that link-specific travel-costs usually vary with flow volume, according to a polynomial volume-delay curve (Sheffi, 1984) which is often link-specific:

$$t_a(x_a) = t_0 + \alpha \, (x_a/c_a)^{\beta} \qquad (3)$$

where t_a is the travel time on link a with flow of x_a and t_0 is the travel time on link *a* with no flow. α and β are constants specific to each individual link. So marginal travel costs can vary widely between links and optimal link flows can change dramatically with a relatively minor change in link capacity, *c.*

Strategic network-planning can include importance by considering a new independent variable for importance, *v,* that is specific to the trip purpose. The following relationship is then constructed:

$$x_a = \sum_{v \epsilon V} x_{a,v} \quad (4)$$

such that travel on link *a* now consists of several different purposes of flow, each corresponding to an independent importance *v*. These types of flows may or may not be determined by the origin-destination pair. In traditional travel-demand models, aggregation of nodes creates many types of flow originating from and destined to a single node. Therefore, the O-D travel will also be defined in terms of importance:

$$q_{rs} = \sum_{v} q_{rs}^{v} \quad (5)$$

A more inclusive assessment of the total travel cost on a link is the product of the flow and the travel time on the link, or the total vehicle-hours of travel (VHTs), $x_a t_a$. Assigning a value to the importance variable *v*, scaled between 0 and 1, can allow the flow volume on each link to be factored by the importance of each trip purpose to produce an importance value for link *a* based on this adjusted travel cost:

$$I_a = \sum_{v \epsilon V} v_v \; x_{a,v} \; t_a \quad (6)$$

for all trip purposes in the set *V*.

Each of the trip types are assigned a value based on the literature and then weighted with an importance value based on this value. This monetized value, m_p, is normalized into an importance-based, unit less "tag", v_p, based on its relationship to the value-of-time for all purposes, P:

$$v_p = m_p \; / \sum_{p \in P} m_p \quad (7)$$

The travel-time-based cost factor used in the original NRI calculation, $x_i t_i$, is modified by the importance of each trip purpose on the link. The system-wide cost, c, is:

$$c = \sum_{i \in I} \sum_{p \in P} v_p t_i x_p \quad (8)$$

such that $\sum_{p \in P} x_p = x_i$

where t_i is the travel time on link *i*, in minutes per trip, x_p is the flow on link *i* due to trip-purpose *p* at user equilibrium (the sum of the flows for all purposes on link *i* is x_i, the total flow on link *i*). *I* is the set of all links in the network. A new variable, v, is a purpose-based importance "tag". *P* is the set of all trip purposes on link *i* at user equilibrium.

The system-wide cost, c_a, after link *a* is disrupted and system traffic has been re-assigned to a new equilibrium, is:

$$c_a = \sum_{i \in I} \sum_{p \in P} v_p t_i(a) x_p(a) \quad (9)$$

where $t_i(a)$ is the new travel time across link *i* when link *a* has been disrupted, and $x_p(a)$ is the new flow on link *i* due to trip-purpose *p*. The same constraint on link flows applies and the mNRI is calculated as the difference between c_a and c.

3.2 Method 3: An Access-Based Formulation

Another way of formulating strategic network-planning is to base the importance of travel on the origin or destination of the trip. “Closeness” is a static descriptive measure relating nodes in a network to links, which means that it can start with a node-importance ranking to derive a measure of link importance. The residual-closeness measure offered by Dangalchev (2006) is found by measuring the shortest paths from the node in question (*i*) to all others in the network with link *a* removed from the network:

$$C_{a,i} = \sum_{j \in J} 1/2^{d_a(i,j)} \quad (10)$$

where $C_{a,i}$ is the residual closeness of link *a* with respect to node *i*, and $d_a(i,j)$ is the shortest-path (in minutes) between node *i* and *j* with link *a* removed, for all other nodes in the network (set *J*). This measure identifies the relationship between a given node and all links in the network. A lower value implies an increasingly “close” relationship between link *a* and node *i*. This process can be repeated for each node in the network, and each link can be weighted according to its “residual closeness” to each node. This weighting can be accomplished by taking the sum of the products of the closeness and the relative importance of each node, v_i:

$$I_a' = \sum_{i \in I} C_{a,i} v_i \quad (11)$$

The drawback of this approach is that it is a static measure that treats travel time as a constant in measuring the shortest-paths between nodes. Therefore, the impact of traffic volume on link travel-time is not considered when ranking links based on critical access. This omission does not adversely affect the results of the analysis if it is combined with a path-based formulation, which includes congestion through the use of a volume-delay function in the network-routing step.

A simplified version of this formulation can be used to identify binary node importance based on the notion of critical access. Facilities to/from which access is critical can be identified and flagged. These facilities might include hospitals, police departments, ambulance dispatch stations and fire stations. In this case, these facilities are rated as “critical” in importance and all other facilities are rated “non-critical.” Critical nodes have a v_i of 1 and non-critical nodes have v_i of 0.

To implement this method, first the shortest paths from the critical destination in question (*i*) to all other destinations in the network are calculated, and a residual critical closeness is found:

$$CC_{a,i} = \sum_{j \in J} 1/2^{d^a(i,j)} \quad (12)$$

where $CC_{a,i}$ is the residual critical closeness of link *a* to node *i*, and $d^a(i,j)$ is the shortest-path (in minutes) between node *i* and all other nodes in the network (set J) with link *a* removed. Subtracting this value from the original closeness calculated with link *a* intact provides a measure of the change in closeness between a critical node and all other nodes in the network:

$$\Delta CC_{a,i} = CC_i - CC_{a,i}$$

A higher value implies an increasingly important relationship between link *a* and critical node *i* because the removal of link *a* has a dramatic effect on its closeness to the rest of the network. This process can then be repeated for each critical destination in the network, and each link is weighted according to its "residual critical closeness" to each critical destination. This weighting is accomplished by taking the sum of these measures of critical closeness for all critical destinations with link *a* removed and subtracting it from the same value for all critical destinations with link *a* intact:

$$CA_a = \sum_{i \in I} CC_i - \sum_{i \in I} CC_{a,i} \tag{13}$$

where CA_a is then known as the overall critical accessibility of link *a*.

3.3 Combined Method

A final access-based NRI (aNRI) can then be derived as the sum of the mNRI as calculated previously and the critical closeness accessibility of link *a*:

$$aNRI_a = mNRI_a + CA_a \tag{14}$$

The sum of the two components of the aNRI is taken because of the prevalence of 0s and negative values in a typical set of NRIs. The impact of the CCA on the final aNRI could then be lost or reversed if the product of these components is used. Using Equation 14, critical destinations are included explicitly in the aNRI along with the effects of re-routing normal traffic, which is imperative because trips to/from critical destinations are omitted from a typical travel demand model.

4 Modifications to the TransCAD Tool

The original development of a scripted tool for calculating link-specific NRIs for a network in the TransCAD software platform is described in an earlier UVM TRC Report, No. 10-009 (Sullivan et. al., 2010). The tool was developed as a scripted add-in macro, called the NRI Calculator, for TransCAD 5.0 in Caliper Script, a complete programming language for designing menus and dialog boxes (including toolbars and toolboxes) and for writing procedural macros. The add-in accepts user inputs and then automatically runs the NRI at one or more selected capacity-disruption level(s) (see Figure 2).

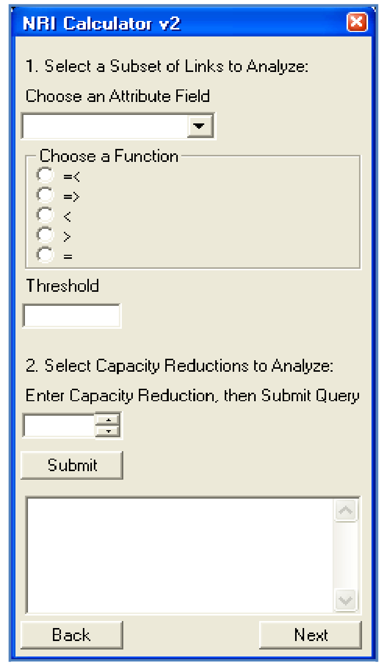

Figure 2 Original TransCAD Add-In for Calculating the NRI

4.1 Modifications for the Path-Based Formulation (Method 2)

The existing tool was modified to allow the input of a purpose-specific importance value. The modification included two general process steps – the first was to modify the traffic assignment type from the standard assignment to the multi-modal multi-class assignment (MMA) and the second was to allow the user-input of importance-based “tags”. The MMA type allows the assignment method selected (e.g., user equilibrium) to be implemented for individual purpose- or mode-specific trip matrices separately. Assigning each trip matrix separately, rather than as one aggregate matrix of all vehicle-trips, preserves “memory” of which trip each vehicle on each link is associated with. Therefore, it is easy to determine, for a total flow of 1,000 vehicles per day on a given link, how many are associated with each trip purpose or mode. This “memory” feature of the MMA assignment model allows importance value “tags”, as given in Equation 7, to be applied to each trip purpose or mode. The tags can then be used to calculate a modified total travel cost, as shown in Equation 8, for generating the new importance-based mNRI.

Each of these steps requires that the user first input the number of separate trip-purpose matrices that will be valued, to set the parameters for the MMA procedure. An input line was added to the initial dialog box, as shown in Figure 3.

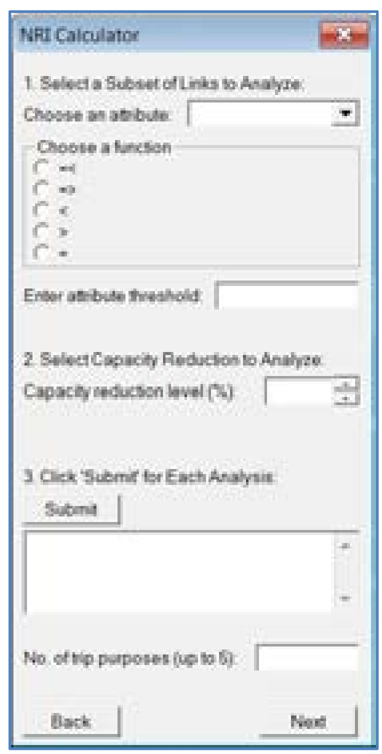

Figure 3 Modified Initial Dialog Box with Trip-Purpose Input

The number of trip purposes that are input by the user is then used to set the parameters for the next dialog box, which now contains a selection drop-down list of the available matrix names and an input for the corresponding importance valuation (factor) for each trip purpose. Figure 4 shows the appearance of the second dialog box, with four (4) trip purposes specified.

Once the appropriate input fields are populated in this dialog box, the macro begins calculating importance-valued, link-specific mNRIs.

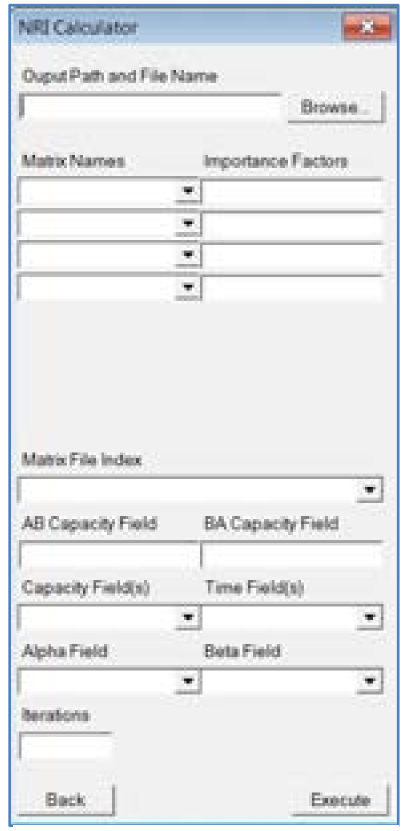

Figure 4 Modified Second Dialog Box with Importance-Factors Input

4.2 Modifications for the Access-Based Formulation (Method 3)

Additional modifications were made to the tool to facilitate the access-based formulation using the additional USDOT funding for this project. The tool was modified to implement the calculation of critical closeness accessibility, as shown in Equation 13. In fact, a new tool was created to solicit the inputs needed to calculate the CA values for every link in a road network, given a set of critical destinations. The new tool requires that the set of critical destinations be expressed as a selection set within the node layer for the road network. In addition, a link selection set must be prepared before the tool is initiated if a subset of all links is to be calculated. Once these selection sets have been created, the tool is opened and the input dialog box shown in Figure 5 appears. Following the prompts the selection set of links to be analyzed is chosen, the attribute field to be minimized (distance or time) is chosen, the selection set of origin nodes (critical destinations) is provided, and the selection set of destinations (all nodes) is provided. Finally, a path and file name for the output file is provided. When the "Execute" button is clicked, a CA is calculated for every link in the selection set, considering the relationship between all critical destinations and all other destinations in the network.

Figure 5 CA Calculator Dialog Box

5 Importance Factors

Each of the approaches for evaluating the strategic importance of links in the Vermont Travel Model network requires using specific importance factors to calculate the final aNRI as shown in Equation (15). In this section, the basis is provided for both the path-based and access-based importance factors selected for use in this study. Three separate path-based factors were modeled and one access-based importance factor was modeled under the portion of the project supported with USDOT funding.

5.1 Path-Based Importance Factors for Method 2

Path-based importance factors are typically based on the value of travel time to users of the network, as it applies to the value of various activities to those users. Following upon the value-of-time research that was described in Section 3.1, we suggest two path-based variations The first approach (referred to as Method 2a) uses a direct value of travel time, which builds upon the NCHRP report (1999) and incorporates defensible default values of travel time which are used in the TREDIS economic-impact assessment software (EDR, 2005):

- Business - \$29.17 per hour
- Commute - \$22.49 per hour
- Personal - \$11.24 per hour
- Freight - \$88.40 per hour

As with the values found in other sources, these roughly reflect the extent to which travel would include or be related to paid work, which invokes consideration of the travelers' wage rate at stake. For freight travel, the value reflects not only the value of the driver's labor, but the value of the commodity being transported. Normalizing each of these values in accordance with Equation (7), yields the following importance factors:

- Business – 0.193
- Commute – 0.149
- Personal – 0.074
- Freight – 0.584

The trip purposes used in the TREDIS system differ slightly from the trip purposes used in the Vermont Travel Model (Sullivan and Conger, 2012). The critical distinction necessary to translate the TREDIS importance factors to the trip purposes Vermont Travel Model ("the Model") was the separation of non-home-based (NHB) trips into business and personal travel. Therefore, the translation of TREDIS trip purposes to the Model trip purposes for Method 2a is provided in Table 1.

Table 1 Translation of TREDIS Trip Purposes to Model Trip Purposes (Method 2a)

TREDIS Purpose	TREDIS Importance Factor	Model Purpose
Business	0.193	NHB-Business
Personal	0.074	NHB-Personal
		HBSHOP
		HBO
Commute	0.149	HBW
Freight	0.584	TRUCK

From the 2009 NHTS, about 21.5% of all NHB trips in Vermont were business related and the rest were more personal in nature. This distinction was used to disaggregate the NHB trips for use in calculating the mNRI.

A second line of research, focused on the utility of time, uses the time spent on an activity as an indication of its general value (Jara-Diaz et. al., 2008). Following this line of reasoning, a second set of path-based importance factors was derived from activity data in the American Time-Use Survey (ATUS) (BLS, 2012). The ATUS is an annual national survey conducted by the Bureau of Labor Statistics that measures the amount of time people spend doing various activities, such as paid work, childcare, volunteering, and socializing. A summary of the data from the 2011 ATUS is provided in Table 2.

Table 2 Summary of National Data in the 2011 American Time Use Survey

Activity	Average Daily Time Spent (min.)
Sleeping	531.31
Personal grooming and self-health-care	45.17
Personal activities	0.32
Non-discretionary household activities	99.98
Discretionary household activities	18.08
Caring for household members	31.33
Caring for non-household members	8.59
Work and work-related activities	158.85
Education	16.29
Non-discretionary shopping	7.57
Discretionary shopping	17.09
Non-discretionary professional services	3.11
Discretionary professional services	1.29
Discretionary household services	0.18
Non-discretionary household services	0.58
Non-discretionary government services	0.30
Eating and drinking	68.30
Socializing and leisure (primarily at home)	289.91
Socializing and leisure (primarily out of the home)	5.84
Participating in sports, exercise and recreation	17.74
Attending sports or recreational events	2.48

Activity	Average Daily Time Spent (min.)
Attending and participating in religious services	13.77
Volunteer activities (primarily in home)	2.64
Volunteer activities (primarily out of the home)	7.29
Making telephone calls	6.39
Travel related to personal care	1.03
Travel related to discretionary household activities	0.31
Travel related to non-discretionary household activities	2.49
Travel related to caring for household members	4.99
Travel related to caring for non-household members	3.73
Travel related to work	12.90
Travel related to education	1.08
Travel related to non-discretionary shopping	5.10
Travel related to discretionary shopping	9.40
Travel related to using discretionary professional services	0.34
Travel related to using non-discretionary professional services	1.42
Travel related to using non-discretionary household services	0.24
Travel related to using discretionary household services	0.09
Travel related to using government services	0.15
Travel related to eating and drinking	7.36
Travel related to socializing, relaxing, and leisure	10.67
Travel related to socializing, relaxing, and leisure (attending)	1.08
Travel related to participating in sports/exercise/recreation	2.04
Travel related to attending sporting/recreational events	0.46
Travel related to religious/spiritual practices	2.14
Travel related to volunteering	1.38
Travel related to telephone calls	0.14
Other traveling	2.19
Unable to code	14.87
Total	1440.00

Sleep was ignored as an activity for use in the development of a second set of factors, since it is a basic human need and not reliant on a specific mode or path of travel. Time spent traveling for an activity was also ignored as an independent activity, so that the relative times spent doing primary activities could be isolated. The average daily time spent on the remaining activities were then converted into normalized values, as shown in Table 3.

Table 3 Conversion of Average Daily Time Spent into Normalized Importance Factors

Activity	Avg Daily Time Spent (min.)	Normalized Importance Factors	Associated Model Purpose
Work	158.5	0.191	HBW
Work-related activities and working travel	0.5	0.001	NHB-Business
Non-discretionary household activities	100.0	0.121	HBSHOP
Eating and drinking	68.3	0.082	HBO
Personal care	45.2	0.055	HBSHOP
Caring for household members	31.3	0.038	HBSHOP
Discretionary household activities	18.1	0.022	HBSHOP
Participating in sports, exercise and recreation	17.7	0.021	HBO
Discretionary shopping	17.1	0.021	HBSHOP
Education	16.3	0.020	HBO
Attending and participating in religious services	13.8	0.017	HBO
Caring for non-household members	8.6	0.010	HBO
Non-discretionary shopping	7.6	0.009	HBSHOP
Volunteer activities (primarily out of the home)	7.3	0.009	HBO
Making telephone calls	6.4	0.008	HBO
Socializing and leisure (primarily out of the home)	5.8	0.007	HBO
Non-discretionary professional services	3.1	0.004	HBO
Volunteer activities (primarily in home)	2.6	0.003	HBO
Attending sports or recreational events	2.5	0.003	HBO
Discretionary professional services	1.3	0.002	HBO
Non-discretionary household services	0.6	0.001	HBSHOP
Non-discretionary government services	0.3	0.000	HBO
Discretionary household services	0.2	0.000	HBSHOP

Since these activities are averaged among all of the respondents' typical work weeks, it is not surprising that work is where most of our time is spent in the U.S., averaging nearly 3 hours a day in a typical week. A final column was added to the table to identify the travel purpose from the Model that is most closely supports the activity. Work activities that are only tangentially related to one's occupation and work-related travel were separated out from the primary Work activity, so that activities related to NHB-Business travel could be isolated from primary work, which is supported by the commuting trip (HBW). The second most frequent set of activities were non-discretionary household activities, like doing laundry. It was assumed that these activities are supported by home-based shopping travel. Other non-shopping activities were assumed to be supported by home-based other (HBO) travel.

The normalized importance factors were then summed according to the Model trip purpose they were most closely supported by, resulting in the set of importance factors for the "Time-Spent" method (Method 2b) shown in Table 4.

Table 4 Model Importance Factors for Method 2b

Model Purpose	Model Importance Factor
HBW	0.191
TRUCK	
NHB-Business	
NHB-Personal	0.543
HBO	
HBSHOP	0.265

A third line of research highlights the significance of constraints imposed on activities by the time of travel required to support them. This research makes use of the "travel-time ratio" as an indicator of the importance of various daily activities (Dijst and Vidakovic, 2000). The travel-time ratio is defined as the ratio between travel time for an activity and the sum of travel time and time spent in the activity. Using the average daily times spent traveling from Table 2 and the time spent doing from Table 3, a series of travel time ratios were calculated, as shown in Table 5.

Table 5 Travel Time Ratios Derived from the 2011 American Time Use Survey

Activity	Doing (D)	Traveling For (T)	TT Ratio (T/T+D)	Purpose from the Model
Work	158.5	12.9	0.08	HBW
Work-related activities and working travel	0.5	-	N/A	NHB-Business
Non-discretionary household activities	100.0	2.5	0.02	HBSHOP
Eating and drinking	68.3	7.4	0.10	HBO
Personal care	45.2	1.0	0.02	HBSHOP
Caring for household members	31.3	5.0	0.14	HBSHOP
Discretionary household activities	18.1	0.3	0.02	HBSHOP
Participating in sports, exercise and recreation	17.7	2.0	0.10	HBO
Discretionary shopping	17.1	9.4	0.35	HBSHOP
Education	16.3	1.1	0.06	HBO
Attending and participating in religious services	13.8	2.1	0.13	HBO
Caring for non-household members	8.6	3.7	0.30	HBO
Non-discretionary shopping	7.6	5.1	0.40	HBSHOP
Volunteer activities (primarily out of the home)	7.3	1.4	0.16	HBO
Making telephone calls	6.4	0.1	0.02	HBO
Socializing and leisure (primarily out of the home)	5.8	1.1	0.16	HBO
Non-discretionary professional services	3.1	1.4	0.31	HBO
Volunteer activities (primarily in home)	2.6	-	N/A	HBO
Attending sports or recreational events	2.5	0.5	0.16	HBO
Discretionary professional services	1.3	0.3	0.21	HBO
Non-discretionary household services	0.6	0.2	0.29	HBSHOP
Non-discretionary government services	0.3	0.2	0.34	HBO
Discretionary household services	0.2	0.1	0.34	HBSHOP

From the table, it is evident that the travel-time ratios are significantly higher for shopping activities than they are for other activities, including work. This finding is consistent with the literature on travel-time ratio and constrained travel (Dijst and Vidakovic. 2000). The travel-time ratios were then again aggregated as shown in Table 6, except that the average for each group was calculated this time instead of the sum. The average travel time ratios were then normalized, resulting in the third set of importance factors used in this analysis, shown in Table 6.

Table 6 Model Importance Factors for Method 2c

<table>
<tr><th>Model Purpose</th><th>Average Travel Time Ratio</th><th>Model Importance Factor</th></tr>
<tr><td>HBW</td><td rowspan="3">0.08</td><td rowspan="3">0.173</td></tr>
<tr><td>TRUCK</td></tr>
<tr><td>NHB-Business</td></tr>
<tr><td>NHB-Personal</td><td rowspan="2">0.16</td><td rowspan="2">0.370</td></tr>
<tr><td>HBO</td></tr>
<tr><td>HBSHOP</td><td>0.20</td><td>0.457</td></tr>
</table>

The importance factors derived from this approach are more equitable than the previous two sets. Less emphasis is placed on work, since business and commuting travel are not shown to be very tightly constrained. Personal travel is considerably more tightly constrained, but shopping travel is revealed as having the highest quantity of travel time relative to dwell time, making it the most important purpose according to the travel-time ratio.

A summary of the importance factors derived from each of the three approaches to valuing travel is provided in Table 7.

Table 7 Summary of Importance Factors for Methods 2a, 2b, and 2c

<table>
<tr><th></th><th>Method</th><th>2a: Based on Value of Time</th><th>2b: Based on Time Spent</th><th>2c: Based on Travel-Time Ratio</th></tr>
<tr><td rowspan="6">Model Purpose</td><td>HBW</td><td>0.149</td><td rowspan="3">0.191</td><td rowspan="3">0.173</td></tr>
<tr><td>TRUCK</td><td>0.584</td></tr>
<tr><td>NHB-Business</td><td>0.193</td></tr>
<tr><td>NHB-Personal</td><td rowspan="3">0.074</td><td rowspan="2">0.543</td><td rowspan="2">0.370</td></tr>
<tr><td>HBO</td></tr>
<tr><td>HBSHOP</td><td>0.266</td><td>0.457</td></tr>
</table>

The increased attention to commuting and business travel is evident in Method 2a, whereas the emphasis in Method 2b is on travel to support leisure activities, and Method 2c is focused on the increased constraints on shopping activities. Based on the various groupings of the Model trip purposes, which suit each of the sets of importance factors, the next step was to group the vehicle-trip matrices accordingly before running the mNRI procedure. For Method 2a, the HBO, HBSHOP, and NHB-Personal vehicle-trip matrices were summed to create a new matrix of all personal travel. For Methods 2b and 2c, HBW, TRUCK, and NHB-Business vehicle trips were summed to create a new matrix of all business-related travel and the NHB-Personal and HBO vehicle-trip matrices were summed to create a new matrix of all non-shopping personal travel.

5.2 Access-Based Importance Factors

Accessibility metrics for critical destinations were used in this study. Therefore, only binary factors were used for the relative importance of each node, v_i, shown in Equation 11. All critical destinations were given an importance value of 1, and all other destinations were given an importance value of 0.

6 Summary of Applications

Each of the augmented importance-based methods was run using the Vermont Travel Model road network with the current (Year 5) travel-demand matrices for 2009-2010. Method 1 (the original NRI approach) took approximately 8 hours to run. With four (4) trip-purposes, the first run of Method 2a took approximately 50 hours. With three (3) trip-purposes, each of the second and third runs took approximately 30 hours. Results were analyzed for the 3,974 links in the Model road network that are not centroid connectors.

Method 3 was run on a network of all public roads and streets in Vermont, so that more specific path-distances could be integrated into the calculation. The network was created from a shapefile of public roads and streets served by the Vermont E911 network, which was downloaded from the Vermont Center for Geographic Information and topologically corrected for this application.

6.1 Summary of Method 2: Path-Based Application

6.1.1 Least Critical Links

For all Method 2 applications, differences between the approaches to quantifying importance were apparent between the rankings at the bottoms of the ranked lists. In fact, when these sets are mapped, there are only 11 links that fall in the 100 least critical links for two approaches, and none that are common to all three approaches. Each of these sets is shown in Figure 5.

Figure 6 100 Least Critical Links in the Rank-Order for Each Importance-Factor Approach

As shown in the figure, each approach to developing importance factors created a different set of the least-critical links in the road network. Method 1 created a set that was focused around the perimeter of the most urbanized area of the state, Chittenden County. Method 2a created a set that is dispersed throughout the rural areas in the southern part of the state, and immediately north and south of Chittenden County. Method 2b created a set that was scattered through the southern part of the state, around the perimeter of the Burlington and Montpelier urban areas, and in the rural northern corners of the state. Method 2c created a set with a fairly uniform distribution throughout the rural portions of the northern part of the state.

Of course, the 11 links in the bottom 100 for more than one method are not apparent in the figure, due to the overlapping of the colored indicators. The links ranked in the bottom 100 by more than one method are provided in Table 11 along with their average ranking.

Table 8 Links in the Bottom 100 by More Than One Method

Road Name	Primary Town	Length (mi.)	Hourly Capacity (vph)	Speed Limit (mph)	Avg. Rank
Ramp to US Hwy 4W	Fair Haven	0.24	1,600	45	3,603
State Rte 78	Sheldon	0.29	1,050	40	3,117
I 91 South	Derby	2.15	4,000	65	3,572
Shelburne Rd / US Hwy 7	Shelburne	0.85	800	40	2,934
I 189 West	S. Burlington	0.31	2,000	45	2,525
Spear Street	S. Burlington	0.25	700	30	3,210
Kennedy Drive	S. Burlington	0.12	1,400	40	2,262
Upper Main St / State Rte 15	Essex	0.09	800	45	2,040
Roosevelt Hwy / US Hwy 2	Milton	0.89	800	50	2,870
US Hwy 7	Charlotte	2.19	800	50	2,075

The links in Shelburne, South Burlington, Essex, and Milton are shown in greater detail in Figure 7. The other links are shown in Figures 8 through 11.

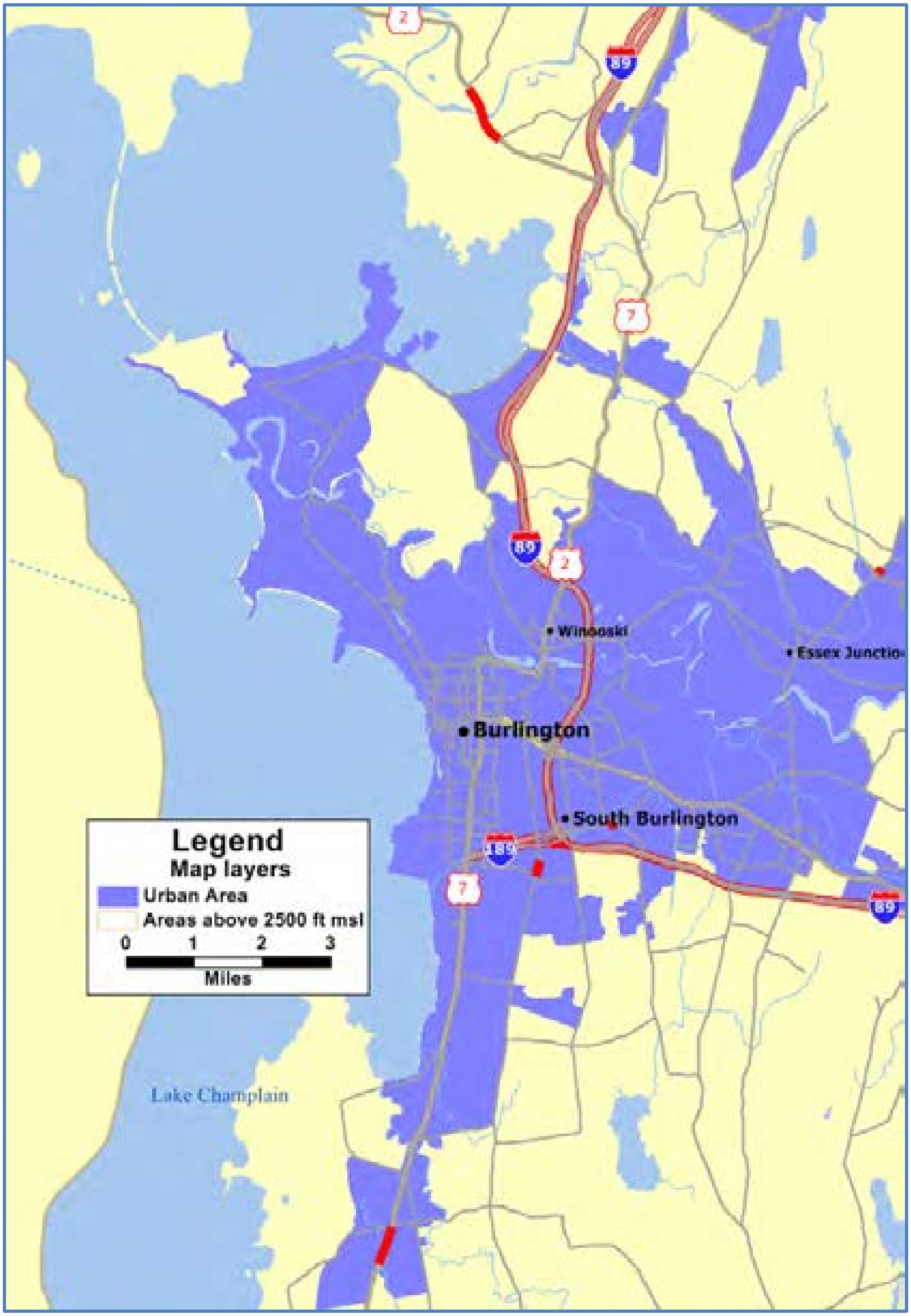

Figure 7 Links in the Bottom 100 by Multiple Methods (shown in red) in the Burlington, Vermont Urban Area

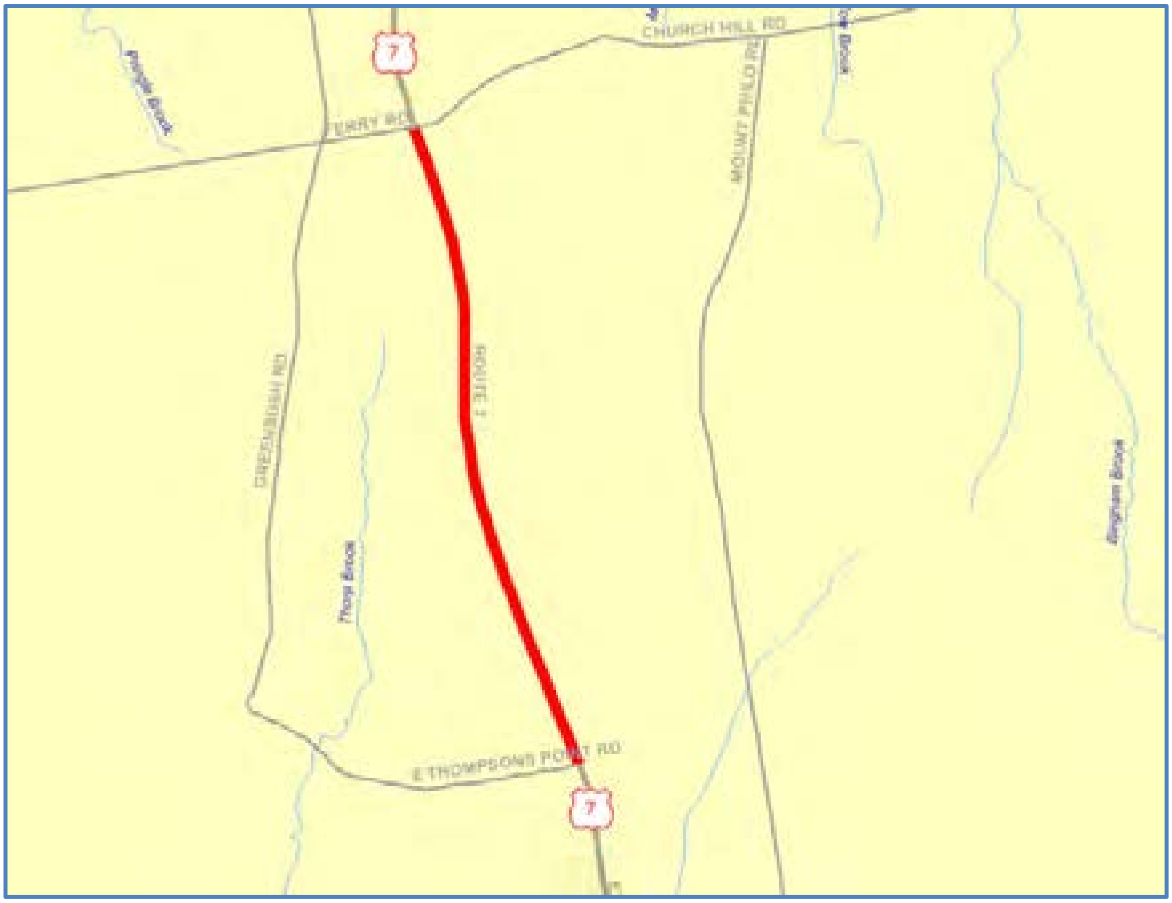

Figure 8 Link in the Bottom 100 by Multiple Methods (in red) in Charlotte, Vermont

Figure 9 Link in the Bottom 100 by Multiple Methods (in red) in Fair Haven, Vermont

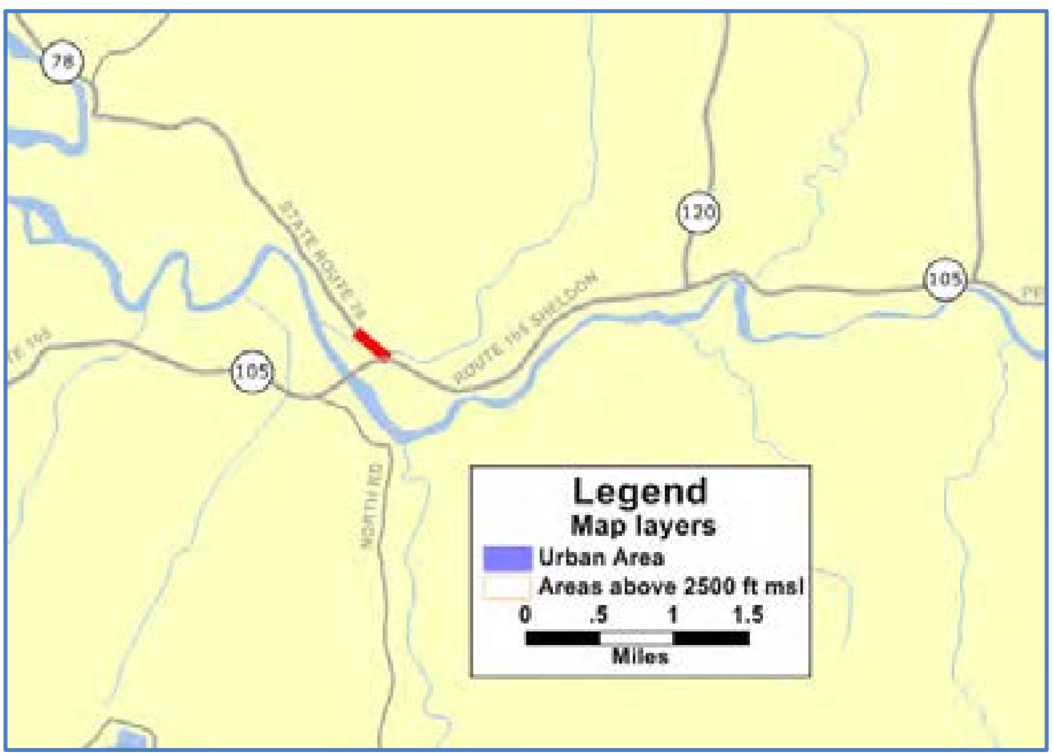

Figure 10 Link in the Bottom 100 by Multiple Methods (in red) in Sheldon, Vermont

Figure 11 Link in the Bottom 100 by Multiple Methods (in red) in Derby, Vermont

Many of the links at the bottom of the rankings are very short segments which represent unnecessary redundancies in the network. The average length of this set of common links is 0.74 miles.

6.1.2 Most Critical Links

When the sets of most critical links in the state by each approach are mapped, 97 links fall into the set of 100 for two or more methods, and 27 of those fall into the set of 100 for all four methods. Each of these sets is shown in Figure 11.

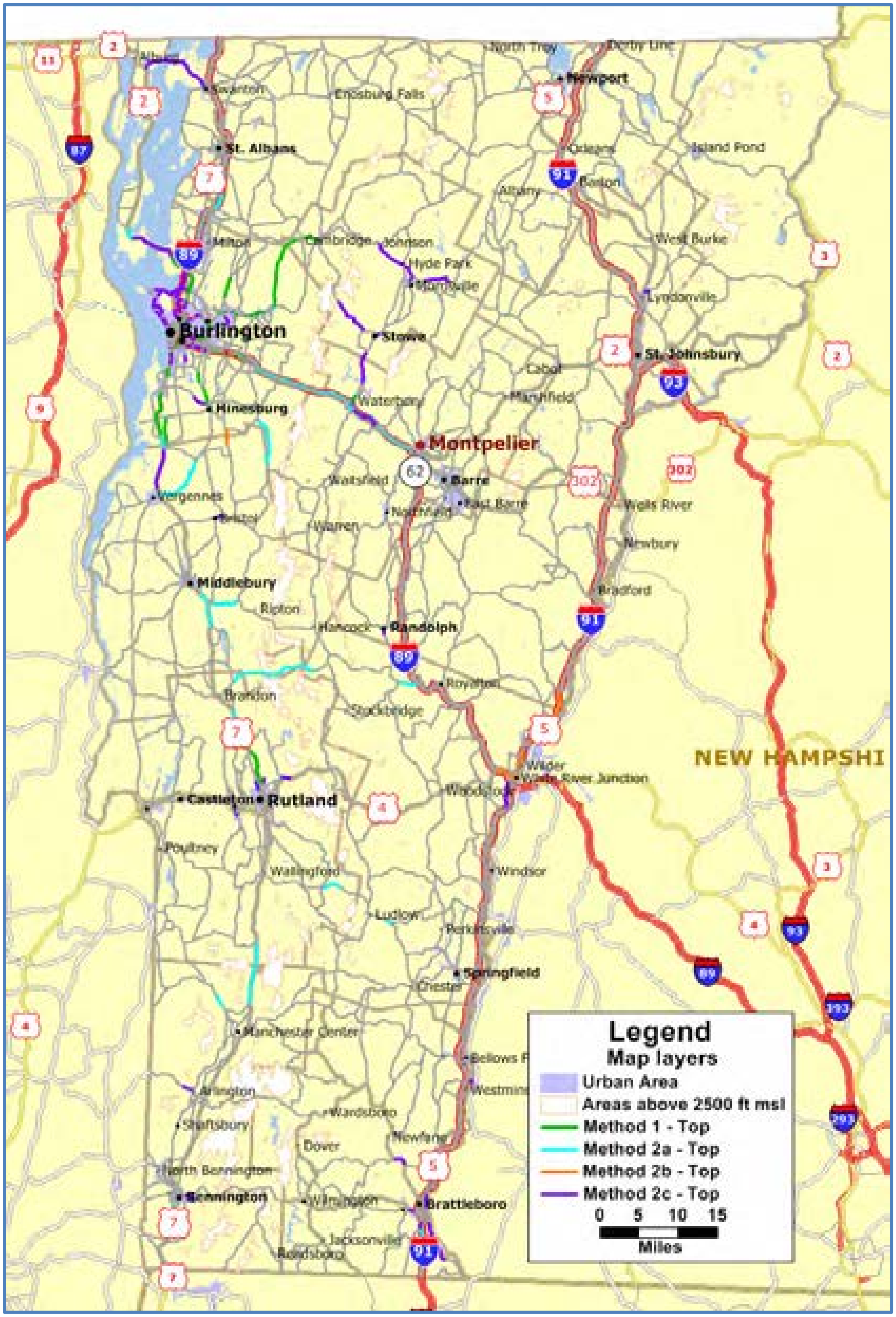

Figure 12 Top 100 Links in the Rank-Order for Each Importance-Factor Approach

Only the differences in the findings for the top 100 links for each method are evident in the figure, due to overlaps in the color scheme. Method 1 resulted in a set of links that was focused around the perimeter of the Burlington urban area. Method 2a resulted in a set of links that are dispersed along the rural portions of the Route 7 corridor and the Green Mountains. Method 2b resulted in a set of links primarily located in the White River Junction urban area. Method 2c resulted in a set of links located within and around the most urbanized county of the state, Chittenden, including the links out to the Lake Champlain Islands. Since they are not apparent in the figure, links ranked in the top 100 by all four methods are provided in Table 13, along with their average ranking.

Table 9 Links in the Top 100 by All Methods

Road Name	Alternate Name	Primary Town	Length (mi.)	Hourly Capacity (vph)	Speed Limit (mph)	Avg. Rank
North Hartland Road	US Hwy 5	Hartford	1.64	1,050	40	42
Western Avenue	State Rte 9	Brattleboro	0.83	1,100	40	39
Putney Road	US Hwy 5	Brattleboro	2.02	1,100	40	36
US Highway 7		Ferrisburg	5.39	1,440	45	31
Roosevelt Highway	US Hwy 2	South Hero	6.36	1,200	40	32
State Rte 100		Waterbury	4.31	1,200	40	49
Veterans Memorial Highway South	I 89S	Colchester	6.05	2,300	65	30
Veterans Memorial Highway North	I 89N	S. Burlington	3.31	2,000	55	62
Shelburne Road	US Hwy 7	Shelburne	0.71	1,600	40	30
Shelburne Road	US Hwy 7	S. Burlington	0.64	1,800	40	39
Shelburne Road	US Hwy 7	S. Burlington	0.28	1,800	35	18
Park Street	State Rte 127	Burlington	0.90	1,000	50	2
North Avenue		Burlington	0.73	7,00	30	19
Heineberg Drive	State Rte 127	Colchester	1.05	1,000	50	54
North Avenue		Burlington	0.50	700	30	10
Pearl Street	State Rte 15	Colchester	0.38	1,600	35	38
Veterans Memorial Highway South	I 89S	S. Burlington	3.03	2,000	55	52
Veterans Memorial Highway South	I 89S	S. Burlington	1.35	2,000	55	40
Veterans Memorial Highway North	I 89N	S. Burlington	1.34	2,000	55	35
Pearl Street	State Rte 15	Colchester	0.55	1,600	35	47
Veterans Memorial Highway North	I 89N	Colchester	6.19	2,300	65	37
Pearl Street	State Rte 15	Essex	0.49	1,600	45	55
Jericho Road	State Rte 15	Essex	0.26	800	30	73

Most of these links appearing in Table 13 are also located in the Burlington urban area, which is shown in greater detail in Figure 13. Some of the links are also located in Hartford, Brattleboro, Ferrisburg, and Waterbury. These links are shown in Figures 14 to 17.

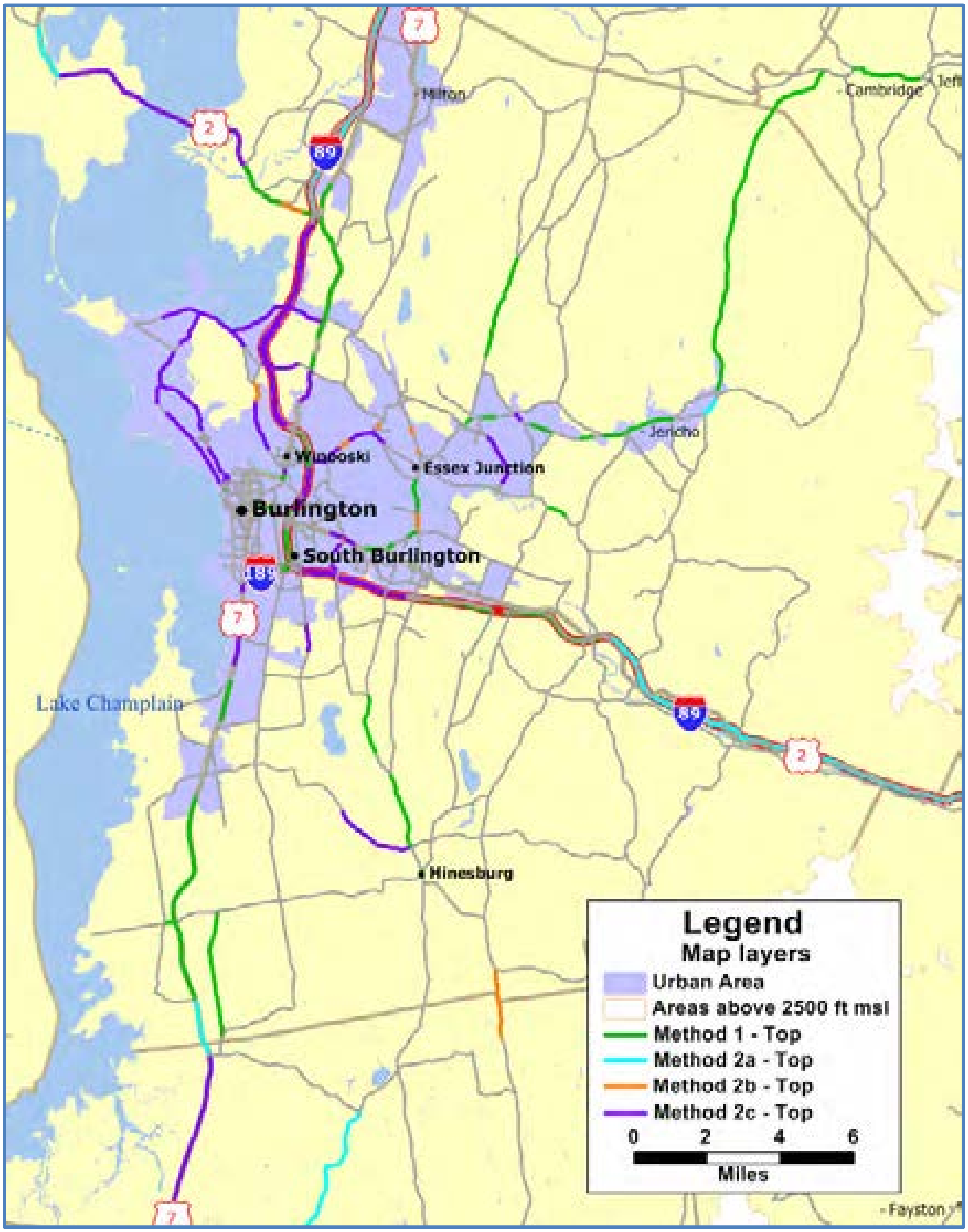

Figure 13 Links in the Top 100 by all approaches in the vicinity of the Burlington, Vermont (shown in purple)

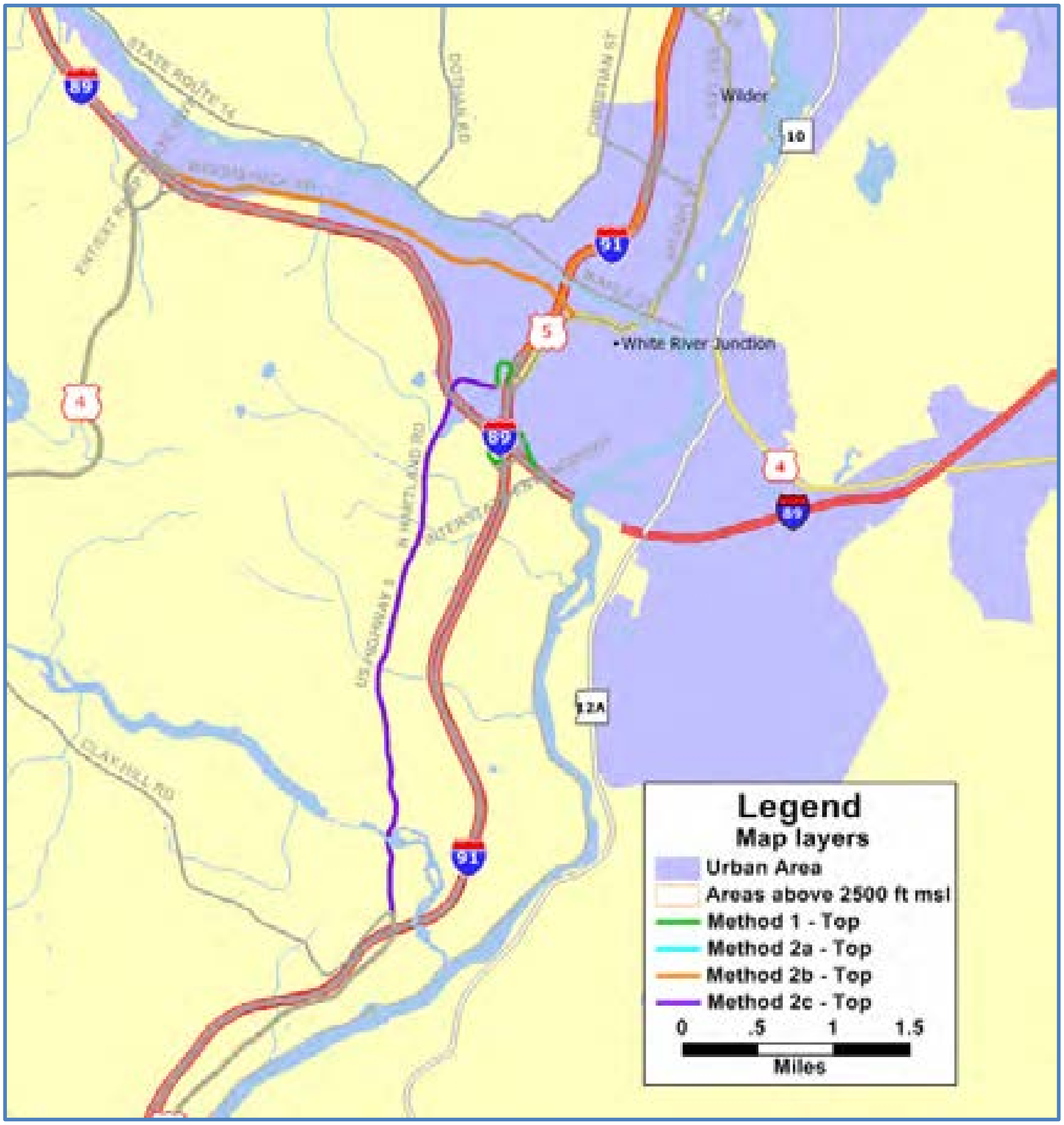

Figure 14 Link in the Top 100 by All Methods in Hartford, Vermont (shown in purple)

Figure 15 Link in the Top 100 by All Methods in Brattleboro, Vermont (shown in purple)

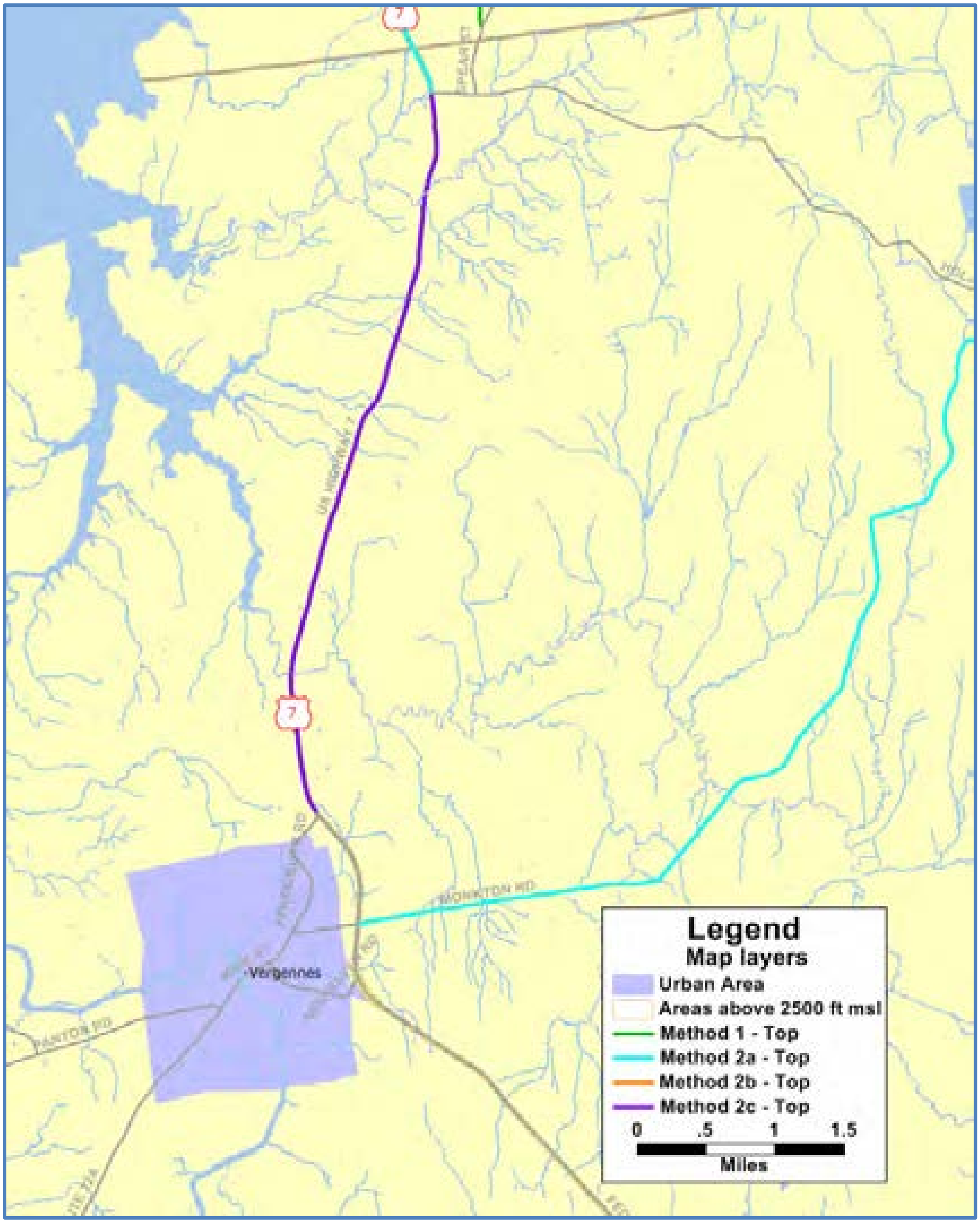

Figure 16 Link in the Top 100 by All Methods in Ferrisburg, Vermont (shown in purple)

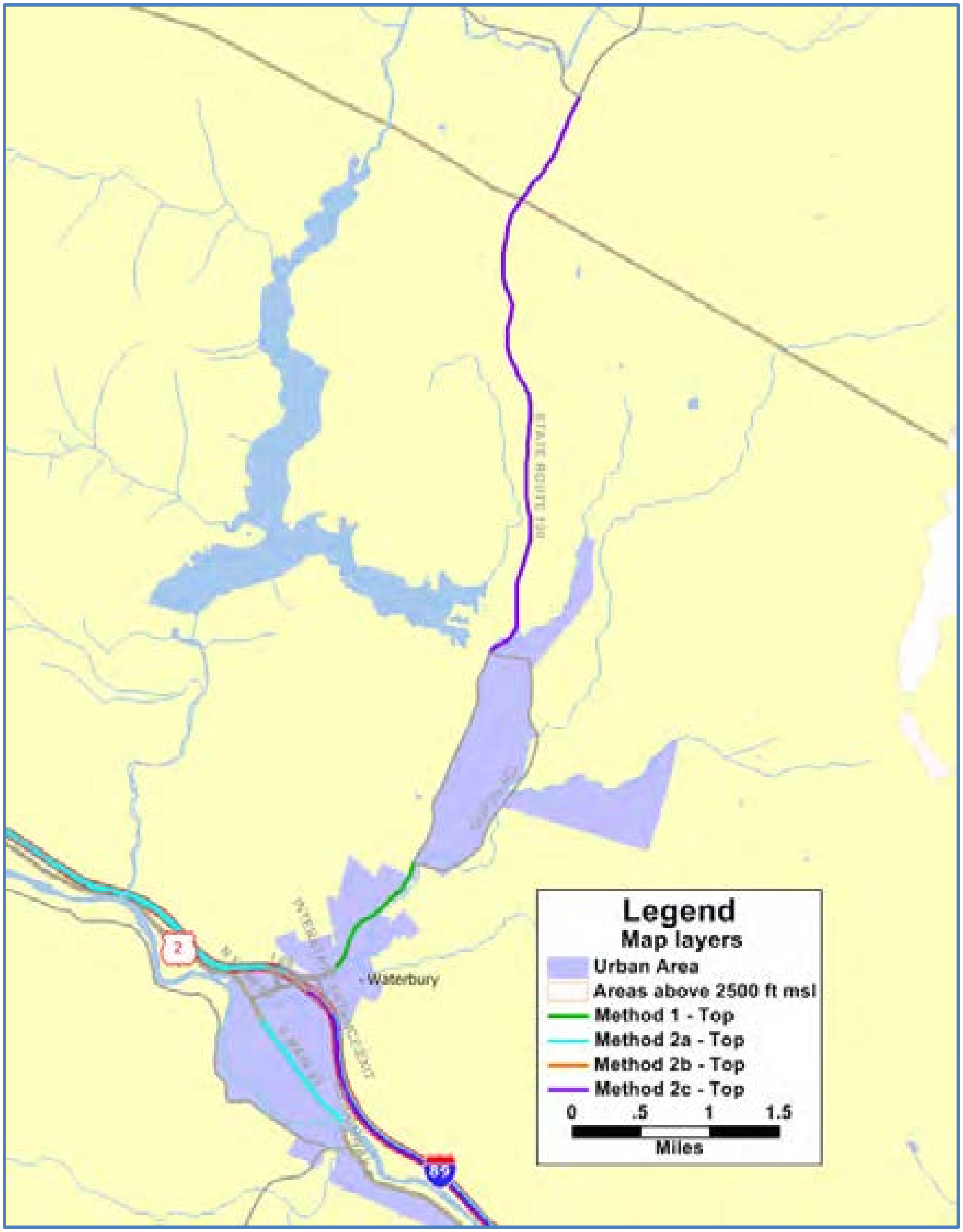

Figure 17 Link in the Top 100 by All Methods in Waterbury, Vermont (shown in purple)

Most of the top ranked links in these lists are longer in length (average of 2.10 miles) and represent bottlenecks in the state's roadway network.

6.2 Summary of Method 3: Access-Based Application

As a stand-alone method of assessing a link's importance to critical-services access, components of closeness and connectivity are included in the solution procedure of the CA. These components of the CA measure are best exhibited in the vicinity of the link with the highest CA in the state, Colchester Avenue / Main Street, which is shown crossing the Winooski River in Figure 18.

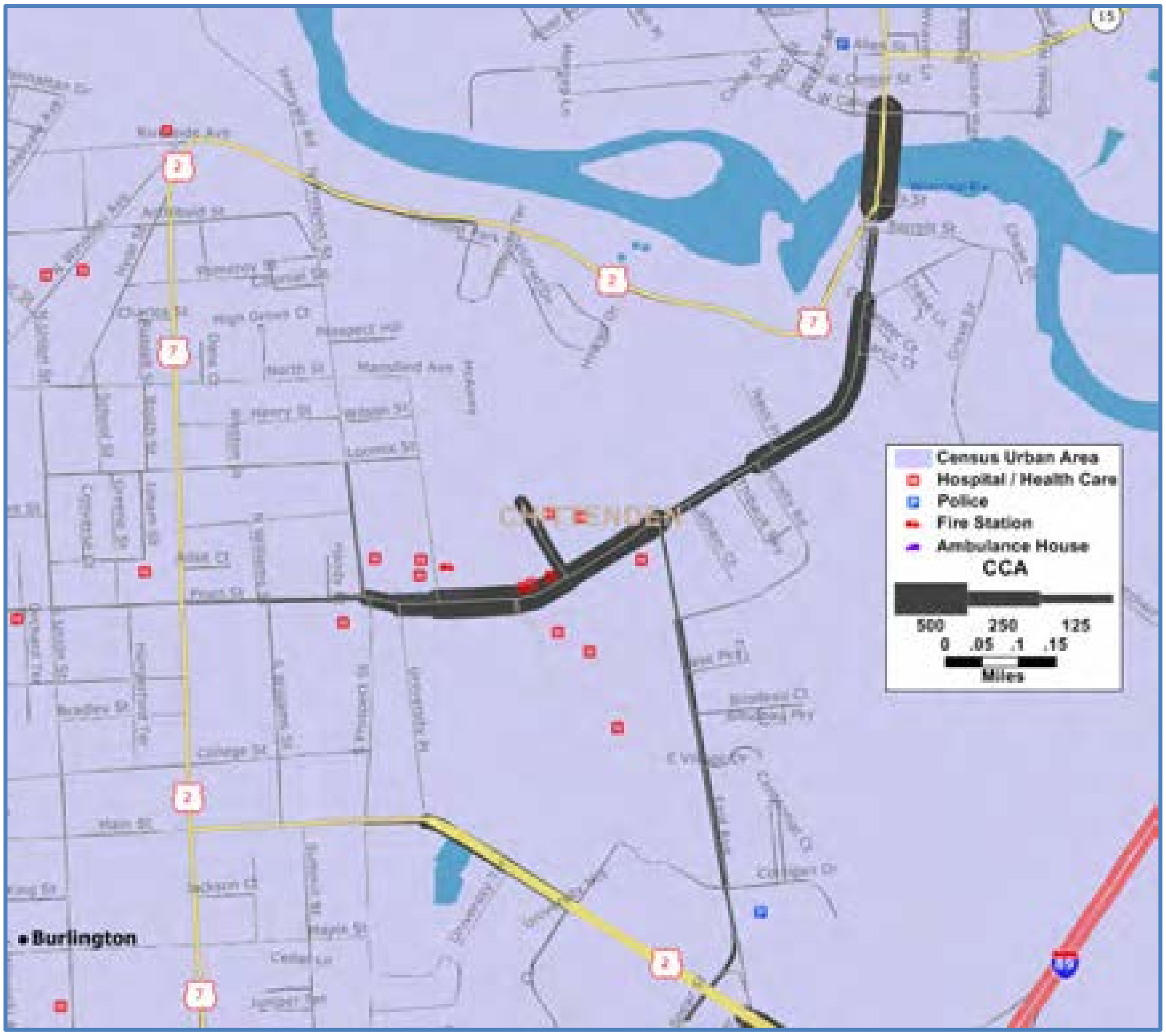

Figure 18 CA Values in the Vicinity of the Highest-Ranked Link in Vermont

The area shown in the figure is centered on the Fletcher Allen Health Care hospital and associated health care facilities in Burlington, Vermont. The hospital is located in a part of the city where roadway connectivity is poor relative to the rest of the city, due to the adjacent campus of the University of Vermont. The central campus of UVM is bounded by East Avenue, Route 2, University Place, and Colchester Avenue, but the university owns land to the north, east, and south as well. The size of these ownership parcels interrupts the grid network present in the downtown Burlington area to the west of the campus. Therefore, the obvious effect of the CA is evidenced by the importance of links close to the hospital complex (along Colchester Avenue, between University Place and East Avenue) but the added effect of the disruption analysis and the lack of redundant connectivity is to point to the bridge over the Winooski River as the most important link in the state with respect to critical accessibility.

This tendency of major hospital facilities to be located in areas of poor roadway connectivity is reinforced by the Rutland Regional Medical Center hospital and health care facilities in Rutland, Vermont. Portions of Stratton Road leading to the hospital, located at the intersection of Allen Street and Stratton Road, also fall in the top 10 statewide when ranked by CA, as shown in Figure 19.

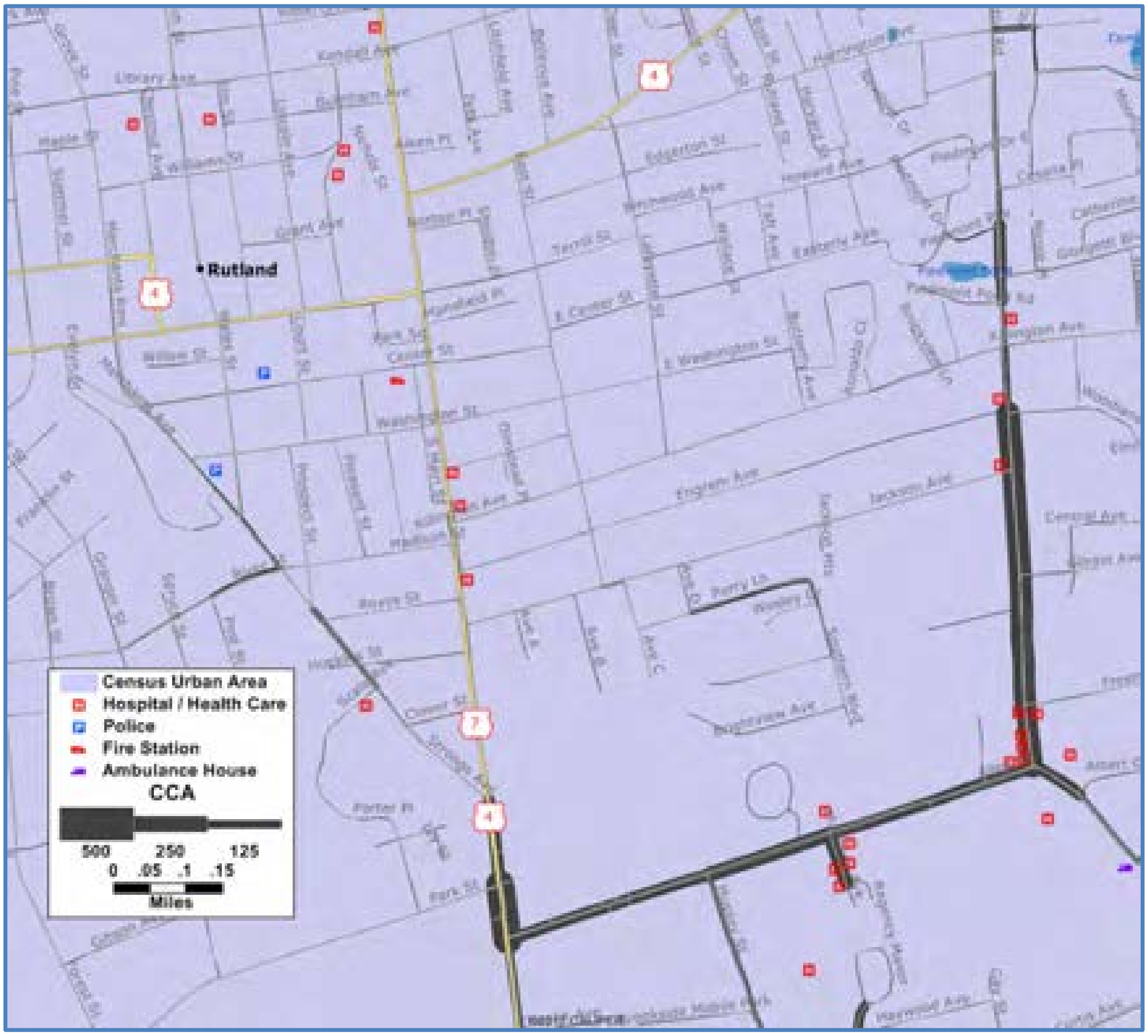

Figure 19 CA Values in the Vicinity of the Rutland Regional Medical Center

Large ownership parcels north and south of Allen Street interrupt the grid network present in the downtown area to the north.

6.3 Comparison of Methods

The results of all method and approaches were compared statistically by the rank orders produced by each of the methods, using the Wilcoxon signed-ranks t-test between ranked variables. Comparisons were made between rank orders resulting from Method 1 of calculating the NRI without trip valuation, Methods 2a, 2b, and 2c of calculating the mNRI with three different approaches to developing trip importance factors, and Method 3 of calculating the CA. A summary of the z-ratios resulting from each comparison is provided in Table 8.

Table 10 Summary of Z-Ratios from the Wilcoxon Signed-Ranks T-tests for All Data

Method	1	2a	2b	2c	3
1		0.91	-0.46	-0.52	2.11
2a			-0.22	0.18	0.42
2b				0.92	0.48
2c					0.26

The critical value of the z-ratio for a p-value of 0.05 is 1.65. Therefore, for all cases except the comparison between Method 1 and Method 3, there is no significant difference between the rankings. However, when we look for correlation in the rankings produced by each method by calculating the square of the Pearson-product-moment correlation-coefficient (r-squared), we find it lacking as well, as shown in Table 9.

Table 11 Summary of R-Squared Values for All Data

Method	1	2a	2b	2c	3
1		0.06	0.04	0.01	0.03
2a			0.07	0.02	0.00
2b				0.02	0.01
2c					0.00

Therefore, although none of the rankings were shown to be significantly different, neither were any shown to be correlated. Additional correlation statistics were calculated for each of the rankings and the variance in the rankings amongst all 4 methods by link.

In this study, we are particularly concerned with the links in the network which demonstrate the highest and the lowest value to the state, because these links are the most likely targets for strategic investment or disinvestment. Therefore, these tests were repeated for the set of 100 links having the lowest and highest average ranks among all 4 methods tested.

The results of these tests for the 100 links with the lowest average rank are provided in Table 10.

Table 12 Summary of Z-Ratios from the Wilcoxon Signed-Ranks T-test for Bottom 100 Links

Method	1	2a	2b	2c	3
1		-77.74	-56.83	53.70	382.00
2a			15.01	51.65	400.20
2b				36.52	413.58
2c					469.04

For all methods, there is a significant difference between the rankings at the bottom of the ranked list.

The results of these tests for the 100 links with the highest average rank are provided in Table 12.

Table 13 Summary of Z-Ratios from the Wilcoxon Signed-Ranks T-test for Top 100 Links

	1	2a	2b	2c	3
1		59.71	56.18	53.73	-254.50
2a			3.01	9.46	-357.73
2b				7.96	-326.61
2c					-369.82

For all methods, there is a significant difference between the rankings at the top of the ranked list. However, the strength of that finding is far less than the differences found at the bottom of the list.

6.4 Combined Method

Consistent with Equation (14), the sum of the Method 1 NRI and the CA was taken, and the results were evaluated. Taking a second look at the area shown in Figure 18, it is now evident in Figure 20 that the aNRI includes the effects of generalized connectivity and traffic flow.

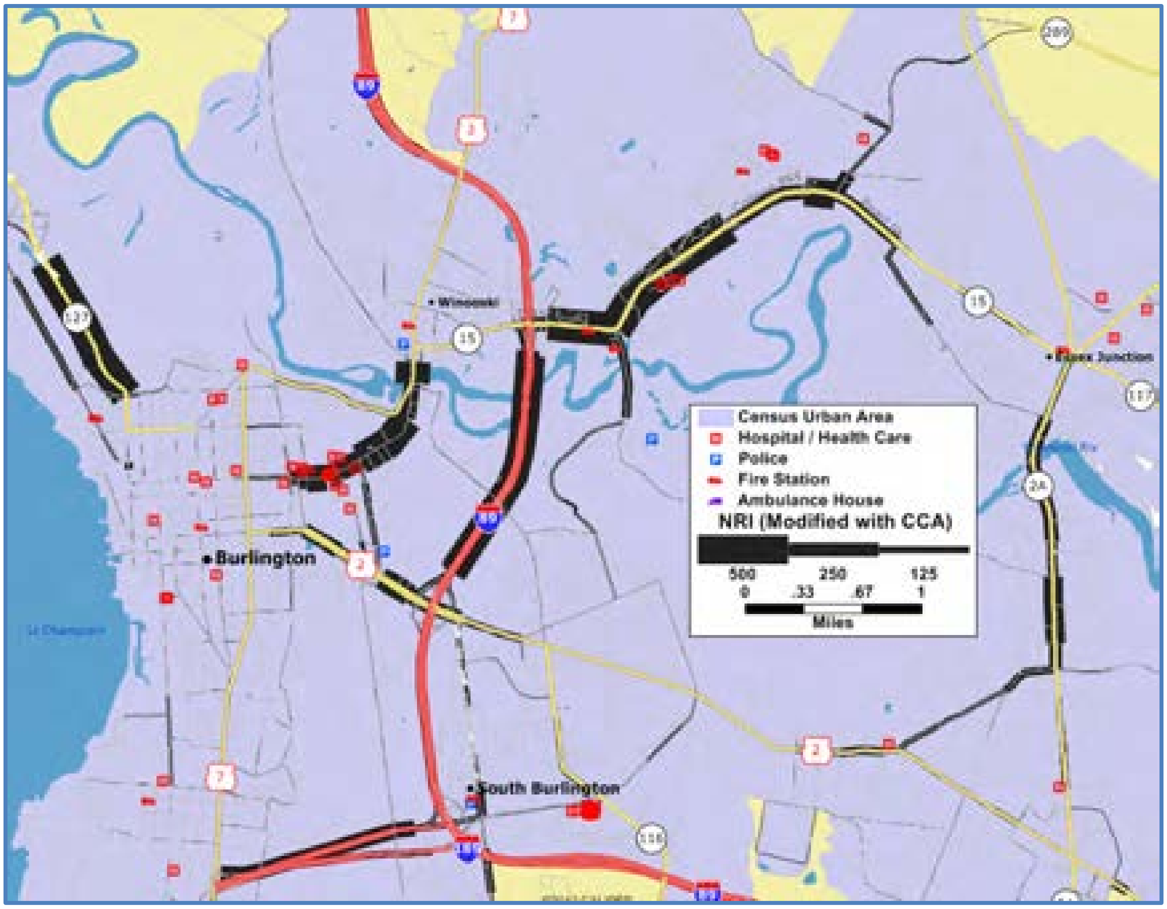

Figure 20 Modified NRI in the Vicinity of the Burlington Urban Area

The link representing Colchester Avenue where it crosses the Winooski River continues to be one of the most critical in the state, but now the importance of links that are not close to emergency service facilities but represent bottlenecks in the network are also apparent. These types of links includes those representing I-89 where is crosses the Winooski River, the link representing Route 127, and the links representing Route 15.

These modifications are less evident in the vicinity of the Rutland Regional Medical Center, where connectivity is better (Figure 21).

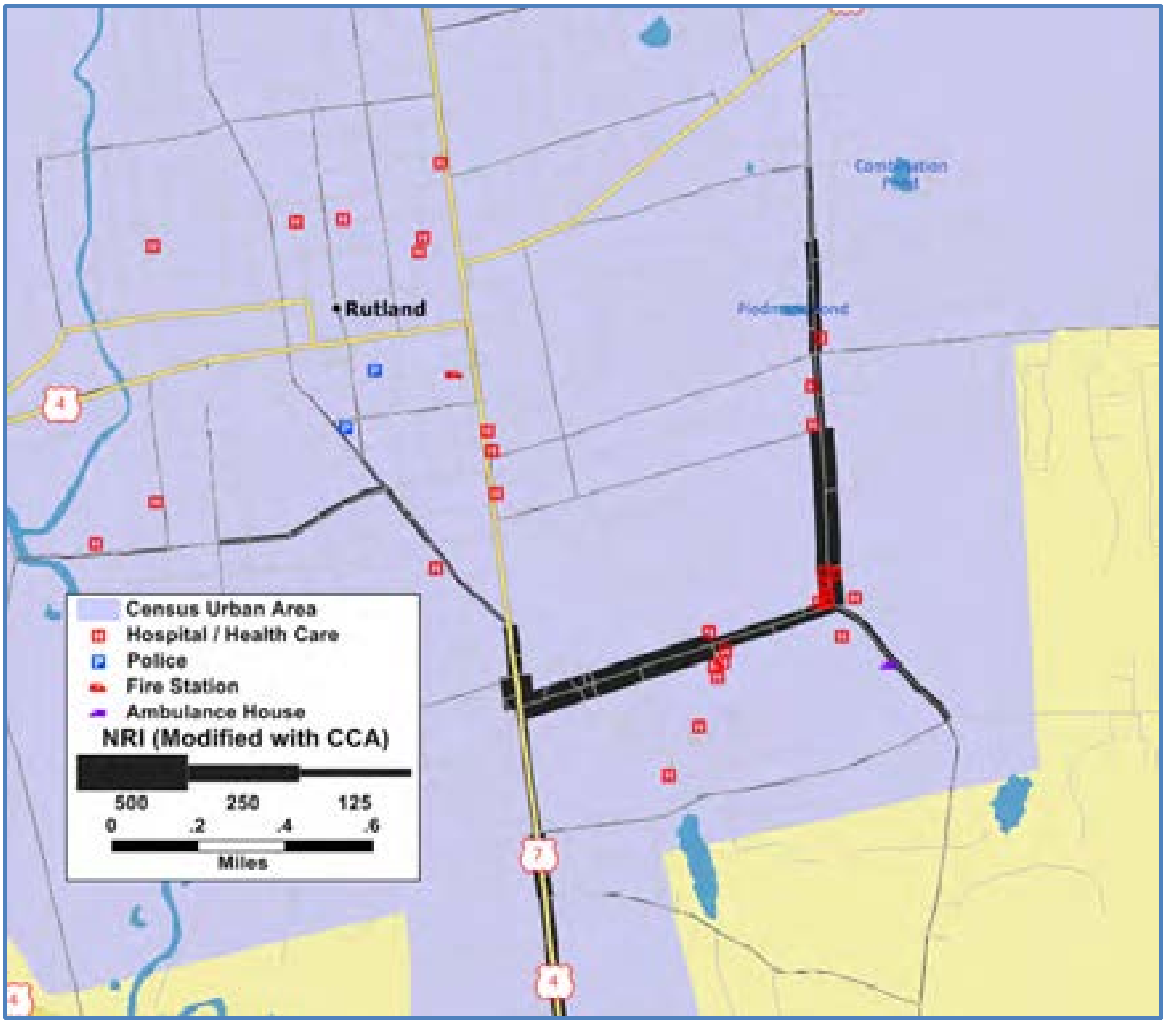

Figure 21 Modified NRI Values in the Vicinity of the Rutland Regional Medical Center

Figure 22 shows the most critical link in the state as measured by the modified NRI (mNRI), near the VA Medical Center in White River Junction.

Figure 22 Critical Links in the Vicinity of the White River Junction VA Medical Center

7 Discussions and Conclusion

7.1 Discussion Regarding the Rank-Ordering of Roadways in Vermont

Based on the statistical evidence presented in this report, the exact method used in valuing travel purposes is critical to the calculation of the most and least critical links in the roadway network. Although the statistical test used did not demonstrate evidence of differences between the rank orders created by each method across all 3,974 links in the roadway network, it did demonstrate statistical evidence of differences in the rank orders at the top and bottom of the lists generated by each method. The top and bottom of the rank orders are presumably the links that are most useful for decision-makers, so this finding is very important.

All of the ranking methods tested in this study (Methods 2a, 2b, 2c, 3, and the Combined Method) produced more defensible rank ordering of the most and least important links in the network than simply assuming that all trips are equivalent in terms of importance (Method 1). Using Method 1, most of the links in the analysis revealed an equal level of importance with an NRI of 0, providing no discernible change in total travel time on the network when disrupted. However, using the methods that included alternate approaches to valuing trips on the network created rank orders without ties, making the overall list more useful for prioritization of links for strategic investment.

Method 2a produced a set of links at the top and bottom of the rank-ordered lists that was more uniformly dispersed throughout the state, and its valuation method is consistent with methods used in other analyses conducted by VTrans which focused on strategic investment (Sullivan, 2013). Therefore, the rank ordering created by Method 2a is discussed in greater detail. Figure 17 shows the top and bottom 100 links in the rank order produced by Method 2a.

Figure 23 Top and Bottom 100 Links in the Rank-Order Resulting from Method 2a

Non-critical links in the state, which might be targets for strategic disinvestment, consist primarily of smaller segments of roadway dispersed fairly evenly throughout the state. Some non-critical links are in areas that are particularly rural and not highly travelled, but others are in more urbanized areas, where excessive redundancies might be present. The bottom 12 least critical links in the state are shown in Table 14 in order of increasing criticality.

Table 14 Bottom 12 Least Critical Links in the State for Method 2a

Road Name	Primary Town	Length (mi.)	Hourly Capacity (vphpl)	Speed Limit (mph)	2010 AADT (vpd)
Colchester Avenue	Burlington	0.20	700	30	11,100
Shelburne Road / US Hwy 7*	Shelburne	0.48	800	40	14,360
North Main St / US Hwy 2	Waterbury	0.00	1,575	40	6,340
US Highway 7	Charlotte	2.19	800	50	10,990
Roosevelt Hwy / US Hwy 2	Bolton	2.92	500	50	2,660
Spear Street	S. Burlington	0.78	700	30	4,900
Ramp to I-89S from 100N	Waterbury	0.19	1,600	30	NA
Upper Main St / State Rte 15	Essex	0.09	800	45	15,250
Ramp from I-89S to Great Brook Rd	Middlesex	0.24	1,600	30	NA
Roosevelt Hwy / US Hwy 2*	Milton	0.89	800	50	9,210
Schoolhouse Road*	Dummerston	2.02	950	30	NA
Spear Street	S. Burlington	0.44	700	30	4,900

Notes:
*** -** denotes a roadway which traverses one or more bridges
NA – AADT not available for 2010

In all, 11 separate towns are represented in the list, further reinforcing that the method does not focus solely on one region of the state, nor does it focus solely on urbanized areas. In addition, the variation of travel on the roadways, as represented by AADTs on these links, reinforces the non-intuitive nature of this metric, with its focus on redundancy and the value of various trip purposes. The lower hourly capacities of these roadways is notable, however, as the tendency for relatively high levels of travel on low-capacity links with a high-capacity redundancy often represents a target for strategic disinvestment.

As noted previously, the least critical links are inherently shorter segments of roadway than the most critical links, indicating that they exist in areas with better roadway connectivity than the most critical links. Also noted in the table are the roadways traversing one or more bridges. These roadways are identified because bridges have an inherently greater cost of maintenance and repair than typical roadway segments, so these links might be particularly strong candidates for strategic disinvestment.

Of final note in the list of the least critical links in the state are two interstate ramps, an entrance ramp and an exit ramp. Most interstate interchanges in the state have a complete set of four ramps to access both directions of travel on the interstate, entering and leaving for each. This analysis demonstrates that, in fact, one of these access ramps is often much less useful than the others. However, it may be the case that leaving one of the ramps off the interchange was not an option when it was constructed. The evolving nature of travel on our interstates may indicate that interstate ramps are a good target for strategic disinvestment.

Also shown in Figure 23 are critical links in the rural parts of the state, which might be targets for strategic investment, are dispersed throughout the Route 7 corridor, from Manchester Center to the Canadian border, as well as in the Route 100 corridor between Waterbury and Morrisville. Notable are also the critical links representing natural “choke points” in the network, including the roadways out to the Champlain Islands, and several passes through the Green Mountains. The identification of these links attests not only to the vulnerabilities created by significant traffic flows on links with little or no redundancy, but the vulnerabilities created by commercial truck traffic using these links. The Method 2a approach to valuing travel puts the greatest value on commercial truck traffic, so many of these links represent roadways that are particularly critical to freight. The most critical links in the state are shown in Table 15 in order of criticality.

Table 15 Most Critical Links in the State for Method 2a

Road Name	Primary Town	Length (mi.)	Hourly Capacity (vph)	Speed Limit (mph)	2010 AADT (vpd)
Fort Bridgman Rd / State Rte 142	Vernon	2.14	1,050	40	4,650
Park Street / State Rte 127*	Burlington	0.90	1,000	50	14,700
State Rte 78	Swanton	5.41	1,440	45	5,310
West Lakeshore Dr / State Rte 127	Colchester	1.02	800	35	11,800
North Avenue	Burlington	1.23	700	30	15,500
Roosevelt Hwy / US Hwy 2*	South Hero	6.36	1,200	40	8,810
US Highway 7*	Ferrisburg	3.31	1,440	45	11,880
State Rte 78*	Alburgh	2.64	1,440	45	4,530
Putney Road / US Hwy 5*	Brattleboro	0.24	1,100	40	15,180
US Highway 5*	Hartland	2.24	1,050	40	3,740

Notes:
*** -** denotes a roadway which traverses one or more bridges

In all, 9 separate towns are represented in the list, indicating that the method does not focus solely on one region of the state, nor does it focus solely on urbanized areas. In addition, although the method tends to focus on heavily-travelled, high-capacity links, the variation in AADTs on these links indicates the additional focus on redundancy and the value of various trip purposes.

Also noted in the table are the roadways which traverse one or more bridges. These roadways are identified because VTrans recognizes the particular challenges inherent to strategic investment in bridges, which typically costs significantly more to maintain and fortify than typical roadway segments. In addition, some of the bridges traverse a waterway, so it is reasonable to expect that an increased probability of inundation from flooding exists for these roadway segments.

The inclusion of the CA to recognize the importance of access to emergency services is also necessary since emergency response trips are not typically included in “business-as-usual” traffic flows. A summary of the most critical links in the state, as measured by Method 3, is provided in Table 16.

Table 16 Summary of the Most Critical Links in Vermont by Method 3

Road Name	Town	Link Length (mi.)	Capacity (vphpl)	Speed Limit (mph)	2010 AADT	Method 1 NRI	CA	aNRI
N. Hartland Rd. / US Hwy 5	Hartford	1.64	1,050	40	3,740	1,393.5	4.4	1,397.9
Pearl St. / State Rte 15	Colchester	0.89	1,600	35	26,520	239.0	415.9	654.9
Main St. / US Hwy 7	Winooski	0.12	1,600	30	27,130	42.9	557.3	600.2
Pearl St. / State Rte 15	Colchester	0.38	1,600	35	21,290	187.8	393.0	580.8
Park St. / State Rte 127	Burlington	0.90	1,000	50	14,700	440.6	113.2	553.8
Colchester Ave.	Burlington	0.37	700	30	11,100	197.9	343.3	541.1
Pearl St. / State Rte 15	Essex	0.17	1,600	45	26,520	75.7	419.2	494.9
Interstate 89 North	S. Burlington	1.34	2,000	55	25,835	431.7	35.6	467.4
Colchester Ave.	Burlington	0.11	1,400	30	14,800	0.0	462.0	462.0
Shelburne Rd. / US Hwy 7	S. Burlington	0.28	1,800	35	31,680	278.6	183.2	461.8
S. Main St. / US Hwy 7	Rutland	0.08	2,200	40	27,720	2.1	431.7	433.8
Shelburne Rd. / US Hwy 7	Shelburne	0.74	1,600	40	17,550	423.0	9.7	432.7
Colchester Ave.	Burlington	0.27	1,400	30	14,800	0.0	376.2	376.2
Interstate 89 South	S. Burlington	1.35	2,000	55	25,835	358.8	40.6	399.4
Main St. / US Hwy 2	Burlington	0.20	2,400	35	41,810	14.6	373.2	387.8
Roosevelt Hwy / US Hwy 2	Colchester	0.64	800	50	9,210	369.3	3.4	372.7
Putney Rd. / US Hwy 5	Brattleboro	1.78	1,100	40	15,000	283.9	82.3	366.1
Canal St. / US Hwy 5	Brattleboro	0.09	1,100	40	11,980	9.5	354.0	363.5
Center Rd. / State Rte 15	Essex	0.18	800	35	13,800	350.4	12.9	363.2
Allen St.	Rutland	0.47	1,100	40	8,600	172.0	190.7	362.6
Linden Ave. / State Rte 30	Brattleboro	0.31	1,100	40	6,410	4.7	352.6	357.2
Western Ave. / State Rte 9	Brattleboro	0.83	1,100	40	14,200	196.9	148.2	345.1
Essex Rd. / State Rte 2A	Williston	0.38	800	40	18,660	238.1	106.9	345.0
Stratton Rd.	Rutland	0.41	1,100	40	9,600	0.9	342.0	342.8

The links included in this list do not differ markedly from those identified by Method 2 as critical (see Table 13), except that certain links that are specifically important to emergency-service accessibility, like Colchester Ave in Burlington and Allen St. in Rutland, are included. The example of Colchester Ave. in Burlington is important because it does not get included with the most critical links by most other methods, and in fact often appears as one of the least critical links in the state. However, its proximity to the largest emergency-service facility in the state (the Fletcher-Allen Hospital and Medical Center) makes it truly a crucial link in the road network.

Perhaps of greater interest in the rank ordering of roadways by Method 3 is the bottom of the rank ordering. The appeal of strategically disinvesting in links that do not exhibit significant importance to the Vermont economy is an ongoing motivation for the rank ordering, and the reason why including access to emergency services was determined to be necessary. The research team working in this field wanted to avoid the possibility of recommending a link for disinvestment when it was, in fact, serving the important purpose of providing access to emergency services.

An increasing focus of policies which consider strategic disinvestment is the presence of bridges on low-value network links. Bridges comprise a much larger investment in a state's infrastructure than land-based roadways. Therefore, a roadway with a bridge represents a greater opportunity for strategic disinvestment policy than one without a bridge.

With these considerations in mind, the roadways at the bottom of the rank order which utilize one or more bridges is provided in Table 17.

Table 17 Least Critical Links in Vermont with One or More Bridges by Method 3

Road Name	Town	Link Length (mi.)	Capacity (vph)	Speed Limit (mph)	2010 AADT	No. of Bridges	aNRI
North Ave. / State Rte 127N Entrance / Exit	Burlington	0.21	900	40	NA	1	-0.72
I 91 North	Brattleboro	0.46	3,600	55	NA	1	0.00
US Hwy 4	Fair Haven	1.78	3,520	65	3,360	1	0.00
N. Goddard Hill Rd.	Westminstr	7.02	1,050	40	760	1	0.00
I 89 South	Swanton	0.30	4,000	65	NA	1	0.00
I 89 South	Highgate	6.20	4,000	65	2,025	1	0.00
Lake Rd. / State Rte 120	Franklin	4.44	1,050	40	910	1	0.00
I 93 North	Waterford	7.27	4,000	65	2,765	3	0.00
State Rte 102	Brunswick	5.24	1,050	40	480	2	0.00
State Rte 102	Bloomfield	3.64	1,050	40	330	1	0.00
US Hwy 7	Highgate	0.37	1,050	40	370	1	0.00
Ethan Allen Hwy / US Hwy 7	Highgate	2.83	1,050	40	540	2	0.00
Berry Hill Rd.	Sheffield	6.21	950	30	NA	2	0.00
I 91 North	Barton	0.37	4,000	65	NA	1	0.00
I 91 South	Weathersfld	0.26	4,000	65	NA	1	0.00
I 91 South	Bradford	0.38	4,000	65	NA	1	0.00
I 91 North	Barnet	0.44	4,000	65	NA	1	0.00
Carter Hill Rd.	Highgate	3.47	1,050	40	670	1	0.00
Valley Rd.	Holland	6.31	950	30	NA	1	0.00
Broad Brook Rd.	Royalton	8.92	950	30	NA	4	0.00
I 89 North	Williamstwn	0.25	4,000	65	NA	1	0.00
Kelley Stand Rd.	Sunderland	13.98	1,050	30	90	6	0.00
Victory Rd.	Victory	7.67	1,050	40	NA	1	0.00
Rupert Rd. / State Rte 153	Rupert	2.94	950	30	NA	1	0.00

Many of the links in this list are not the responsibility of VTrans, so they would nt be realistic candidates for disinvestment. However, they represent linkages between roadways that are maintained by VTrans, so their level of importance is worthy of consideration in any disinvestment scenario. Of particular note in this list is Kelley Stand Rd., which traverses at least 6 bridges in its course through the Green Mountain National Forest between the towns of Stratton and Sunderland, as shown in Figure 24.

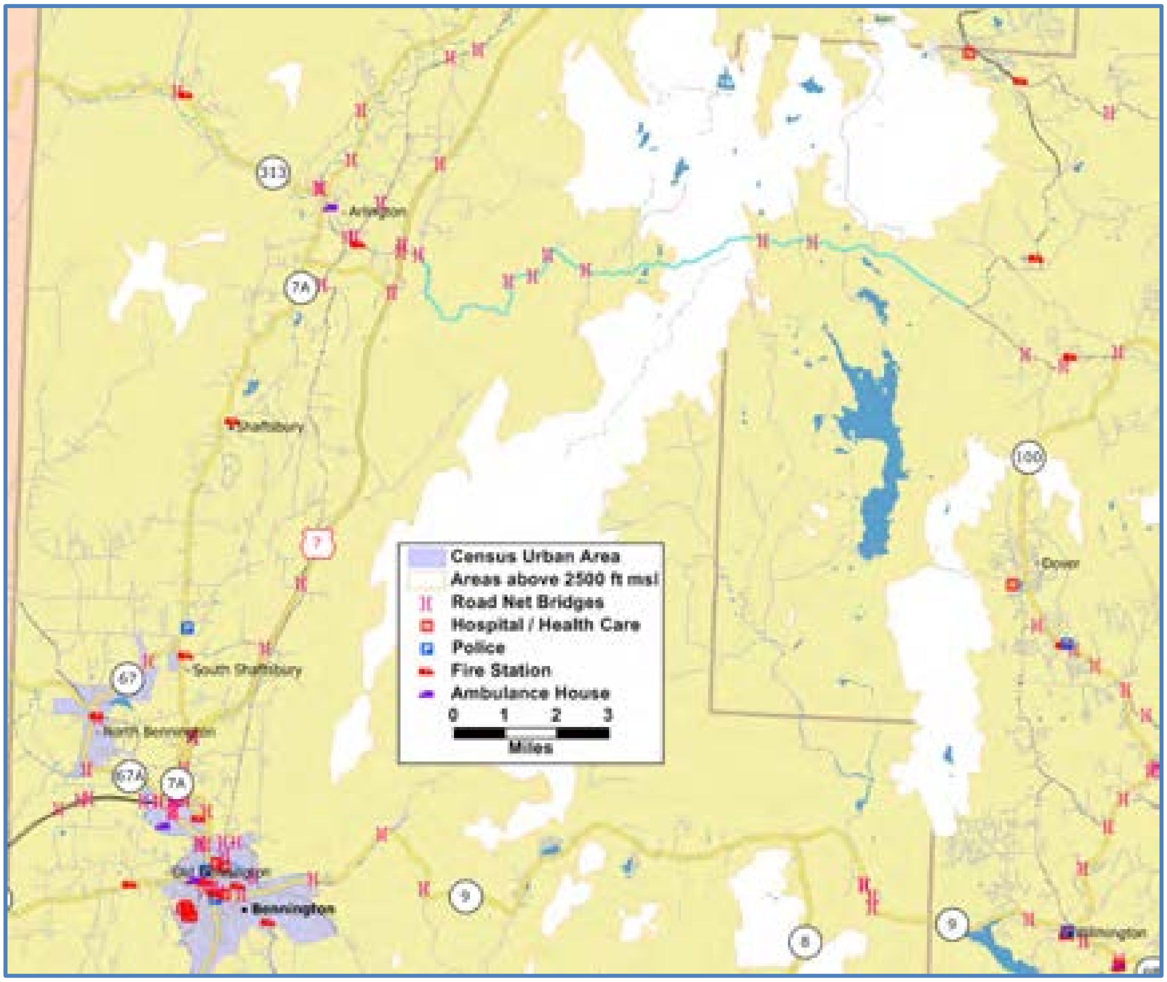

Figure 24 Kelley Stand Road (Shown in Turquoise) in Southern Vermont

The 2010 AADT for this road was 90 vehicles. This consideration, along with the number of bridges it requires, indicates that its maintenance cost might not add value to the Vermont economy. Disinvestment in this linkage is not a consideration for VTrans, since it is not the Agency's responsibility. However, it represents a poignant example of how investment in the transportation system must be reconsidered.

7.2 Discussion Regarding the Use of Travel Importance in Strategic Transportation Planning

The notion of variable trip importance is controversial, since it creates a distinction in the network between trips that are going to be valued highly, and those that are not. The controversy comes when it has to be determined which trips are to be considered more essential to the system. Trips made by emergency vehicles are already implicitly given preference over other types of trips through the use of lights, sirens and, in some cases, traffic signal control. Should critical freight trips be included as well? What about commuting traffic? Should the value of time vary for different users?

There may be significant resistance to promoting the protection of one type of travel over another, when the road network has traditionally been equally accessible for all trips. Politically-charged examples of this controversy exist in the literature (Mackie, 2003; Bradshaw, 1992) and are becoming more prevalent with the proliferation of congestion pricing, which is itself a form of trip purpose valuation. It may be possible to resolve these controversies if input is solicited from a variety of stakeholders such as:

- Municipal Planning Organizations (MPOs) and Regional Planning Commissions (RPCs)
- Neighborhood Associations
- Citizen Planning Groups
- Non-Government Organizations (NGOs)
- Local Economic Development Agencies
- Regional Business Investment Groups

Additional research will be needed to determine the best strategies for implementing measures of importance in the public sector. Incorporation of a destination-based importance, for example, may require a ranking of the nodes in the network. Statistical methods may be necessary to assimilate a multitude of rankings from a variety of stakeholders.

7.3 Conclusion

In this project, the research team advanced a new type of system-wide measurement of link criticality that provides the information needed for strategic disinvestment in roads that are not critical to the health and welfare of Vermonters. The original NRI methodology was refined to include a process for considering the reason for travel in valuing roadways in Vermont, resulting in the mNRI, and a further modification was incorporated into the NRI calculation procedure using a new measure of accessibility to emergency services, the CA. Three new approaches to valuing the reason for travel were tested and the results were compared to one another to ensure independence.

The new measures were found to provide useful complimentary information about the value of roadways in the state. The use of these new measures in the public sector requires a paradigm shift in our current planning function and in the methods used to measure the importance of transportation system components. The measures described in this proposal combine strategic, operational, and security objectives into a single planning measure.

In addition to this comparison, an in-depth analysis of the links that fell in the bottom and the top of the ranking was conducted, with recommendations for links to consider for disinvestment. When combined, the mNRI and the CA produced a new metric, the aNRI that was effective for identifying the roadways in Vermont that are least critical to the state's overall economic well-being. Focusing on the bridges on the least critical links for disinvestment provides a defensible approach to strategically strengthening the state's funding future for maintenance and operation of its assets.

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