Critical links supporting Vermont's bulk milk transportation: a novel application of the Network Robustness Index

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ABSTRACT

The network robustness index (NRI) has been proposed as a more holistic approach to prioritizing road segments for maintenance, improvement, and protection. The utility of this index for identifying segments of importance for freight or any other transportation has not been tested. This project applied the index to a data set representing milk flows in northwestern Vermont. Data for bulk milk collection routes were collected using geo-loggers carried on each truck. A TransCAD street layer was used as the base network and farms were associated with nearest pre-existing nodes. An origin-destination matrix representing two days of milk flows was used to calculate the NRI with TransCAD. For assessing the costs in the case of milk flows, the authors used units of pound-hours, which expressed the dual importance of milk transport volumes and their corresponding travel times. When the model was run, a baseline system-wide total pound-hours of milk flow was first calculated; then the increase in pound-hours of milk flow was calculated as individual links in the network were removed. Links associated with a higher “cost” to the system when removed received a higher ranking in terms of criticality. Using the NRI as a measure of system-wide network reliability and flexibility and to identify critical links in the movement of bulk milk may help state agencies or towns prioritize road investments to support the movement of this economically important freight. This information can also help milk handlers and regional cooperatives engage in emergency contingency planning.

INTRODUCTION

The food supply chain is an interwoven network consisting of producers, processors, manufacturers, distributors, retailers, and consumers. With the exception of direct marketing or community-supported agriculture systems, some or all of these intermediaries are involved. In all cases, links between each member of the supply chain are subject to disruption. A disruption in transit of goods between any of these points, be it a detour, poor road condition, theft, accident, or major disruption caused by natural, accidental, or intentional catastrophe can have consequences ranging from reduced efficiency of operations to total loss of value of product (if stolen or highly perishable). Given that the food and agriculture sector was declared a critical infrastructure by Homeland Security Presidential Directive 9 (*1*), ways to assess vulnerabilities and prioritize mitigation strategies are needed.

The interconnected nature of the food and agriculture system has been recognized and a new tool developed to assist with sector assessments. The Food and Agriculture Sector Criticality Assessment Tool (*2*) developed by the Center for Food Protection and Defense at the University of Minnesota has been adopted by the U.S. Department of Homeland Security for states to use in prioritizing critical assets in this sector. With the tool, food and agriculture system or sub-system nodes can be compared with one another to rank their criticality and prioritize vulnerability assessment and mitigation actions.

Similarly, a tool is needed to identify critical links given the interconnected nature of the transportation system underlying the movement of food and agricultural products. The Network Robustness Index (NRI) (*3*) provides such a system-wide approach to identifying critical links and evaluating transportation network performance. The theoretical framework of the NRI accounts for network-wide demand and traffic re-assignment. It may prove a useful approach for evaluating critical links for freight commodity or any other transportation flows.

The objective of this project was to apply the NRI for the first time to a real-life data set of freight transportation flows over a real road network. Application of the NRI to Vermont milk transportation networks would help focus attention on links critical to the overall performance of the road infrastructure serving the raw milk supply chain. The paper presents the analysis of a data set reflecting milk movements in northwestern Vermont.

BACKGROUND AND JUSTIFICATION

The food and agriculture sector [as defined by The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets; (*4*)] accounts for roughly one-fifth of the Nation's economic activity [according to the National Agricultural Statistics Service, cited by (*5*), when accounting for all inputs necessary to put food on the tables of consumers at home and away from home]. Security best practices that should be in place throughout the food supply network have been suggested, such as (*6, 7*). Likewise security guidelines published by the U.S. Department of Agriculture with input from the Agricultural and Food Transporters Conference and Conference of American Trucking Associations (*8*) pertain to issues in transit. Neither of these guidelines addresses food safety or product loss issues that would arise in the event of infrastructure failure from any type of major catastrophe. A safe and secure food system depends on the integrity of the infrastructure connecting producers to consumers and every step in between.

Vulnerability as usually defined has to do with a characteristic of the item or system "at risk." Risk has various definitions depending on context and perspective [for instance, (*9-12*)]. Important components of a definition of risk when conducting risk assessments are an estimate of probability and of consequence. As applied to transportation networks, "the criticality of a certain component (link, node, groups of links and/or nodes) in the network involves both the probability of the component failing and the consequences of that failure for the system as a whole." (*10*) Jenelius et al. (*10*) also argue "that a reasonable measure of the reduced serviceability/operability/accessibility is the increase in generalised cost of travel."

Ways to assess the vulnerability and performance reliability of transportation infrastructure have multiplied since transportation was declared a critical infrastructure in terms of homeland security. Infrastructure disruptions may result in impaired capacity or complete loss of connectivity among links.

When applying accessibility-based methods (*13*), more vulnerable road links have greater socio-economic value. Husdal (*14*) suggests that this approach could apply equally well to identifying important links in supply chains.

Supply chain risk management is clearly one aspect of business continuity planning (*14*). Just-in-time inventory management has been embraced widely for its positive impact on reducing costs of storing and moving inventory. However, it only works well as long as everything is working fine in suppliers' operations and during delivery. A stop movement order that could be declared in a food or agricultural emergency to stop the spread of a disease or pest would certainly impact dependent supply chains and potentially the continuity of affected businesses.

A best-practice supply chain is likely to be robust, flexible and resilient (*14*). As defined by Asbjørnslett and Rausand, 1997, [cited by (*14*)], a robust network can accommodate uncertain future events without adaptation; a flexible network can accommodate and successfully adapt to changes in the environment; a resilient network is able to survive changes despite severe impact. As noted by Husdal (*14*), "supply chain resilience is not only a function of organizational preparedness, it is also a function of supply chain design."

The NRI was proposed as an alternative to the link-based volume to capacity ratio for identifying critical links in a highway (*3*). The NRI is a way to rank the criticality of individual links based on the consequence to the whole network of removing a particular link. This method accounts for both network-wide demand and traffic re-assignment in determining the cost of lost (or diminished) link connectivity. As proposed, this cost is expressed as change in travel-time between network performance with all links functional and performance with a link removed or impacted. An NRI is calculated for each link in the road network of interest. High values of NRI indicate a high cost in terms of system travel time when a particular link is impacted. When considering full link removal, the NRI is actually an inverse measure of resilience as defined in (*14*). The use of the NRI is in keeping with the concept of conditional criticality in assessing risk and utilizing network information to estimate the consequences network-wide. Such information is needed to assess supply chain risk and develop continuity of business plans.

The NRI would be a novel approach to assessing supply chain transportation networks in the context of agricultural freight. Farm products and food are among the top 5 commodities by tonnage and dollar value transported by truck in Vermont (*15*). Among farm products, raw bulk milk is the most valuable agricultural commodity, contributing up to 70% of agricultural farm gate receipts (*16*). Thus, a data set was obtained so that the NRI could be applied to determine critical links supporting milk flows in the state. Such information could facilitate investment in road segments and increase the resilience of the food system.

METHODOLOGY

The NRI was calculated using TransCAD version 5.0 with an actual road network and a realistic origin-destination matrix. The road network was developed from the street map layer for 3 counties in northwestern Vermont—Chittenden, Franklin, and Grand Isle.

Road Network

The 3-county region encompasses all of the farms in the data set, all of the roads they normally travel on, and all of the possible alternate routes of travel for these trips. The streets files from TransCAD do not include some of the required fields which are used to calculate the NRI, i.e., capacity, free-flow speed, and free-flow travel time. However, the Census Feature Class Codes (*17*) for road type are included in the data set. From these road classes, it was possible to infer the capacities and free-flow speeds of the road in the network from other available information. The values shown in Table 1 were taken from known values for roads common to the TransCAD streets file and the one included in the Vermont Statewide road network, compiled for base-year 2000 (*18*). Road lengths are provided in the streets data set, so a final field for free-flowing travel time was calculated by dividing the road length by its free-flow speed. The geographic layer for the farms in the milk transport network was overlaid on the street network, and the intersection or endpoint nearest to each farm location was selected as the farm location for the purposes of calculating the NRI. By mapping farms to nodes on the streets network, it became unnecessary to create centroids for the network, and more accurate locations for the farms could be used.

TABLE 1 Capacities and Free-Flow Speeds by Road Type Code[a]

Road Type	Description	Capacity (vph[b])	Free-Flow Speed (mph[c])
A41, A43, A45, A49	Local, neighborhood, and rural roads	800	35
A31, A33, A35, A39	Secondary and connecting roads	1000	40
A21, A23, A25, A29	Primary roads without limited access	1200	40
A11, A15, A17, A19	Primary highways with limited access	4000	55

[a]Road type codes A41, A43, A45, etc., correspond with Census Feature Class Codes (*17*)
[b]vph = vehicles per hour
[c]mph = miles per hour

Origin-Destination Matrix

As originally conceived for calculating NRI, the origin-destination matrix represents the volume of traffic between each demand node in the network, identified as either the origin or the destination of a particular trip. For the specific application to milk transport in northwestern Vermont, the origin-destination matrix consisted of pound-trips of milk over a 2-day analysis period. An inferred estimate for pounds of milk carried node to node was entered in the origin-destination matrix. For example, if 2 trips of 25,000 and 12,000 lbs of milk were made from a certain origin to a certain destination over the 2-day analysis period, then the demand for that origin-destination pair was set at 37,000 lb-trips. Actual data on milk transport were used to infer demand for milk between all of the nodes in the network. The data were based on bulk milk-pick-up routes recorded in July and August of 2008. Milk truck drivers were asked to complete a short survey and carry a passive geo-logger until all of their routes had been completed. Two days worth of data were then combined in the origin-destination matrix to account for the fact that some farms have milk picked up every day and some only every other day. The pattern of milk routes is repeated every 2 days, regardless of day of week. The routes included in this pilot analysis were primarily delivering to a single location in St. Albans.

In populating the origin-destination matrix, most farms were both destinations and origins to reflect the “receipt” of milk from the previous stop on the route and “production” of milk headed to the next stop. The estimated demand volumes increased linearly based on number of stops on the route and estimated load volume (from driver survey). The process of inferring the origin-destination matrix from actual GPS transport data reverses the normal travel-demand modeling process, but is necessary for evaluating links critical to commodity flow.

Because the NRI as currently formulated can only be calculated for freight commodity flows if alternate routes are available, routes that included stops that would have been orphan nodes relative to the sub-network of interest were excluded from the origin-destination matrix. To allow inclusion of final legs of routes, where the milk destination is an effective “sink” for travel demand, all remaining nodes were included in the final analysis. Following the preparation of the origin-destination matrix, a traditional traffic assignment was run using the pounds of milk per hour instead of vehicles per hour. A user-equilibrium assignment (*19*) was performed, but steps were taken to avoid the simulation of congested conditions. User-equilibrium traffic assignment is a mathematical method of predicting the routes that will be taken between each origin and destination. The solutions for this method reflect the economic theory that travelers between a given origin-destination pair will adjust their routes until all of their travel times are equal (even though they may be taking different routes to get from A to B). The total milk flows for this dataset resulting from the traffic assignment are represented by the thickness of the roads in Figure 1.

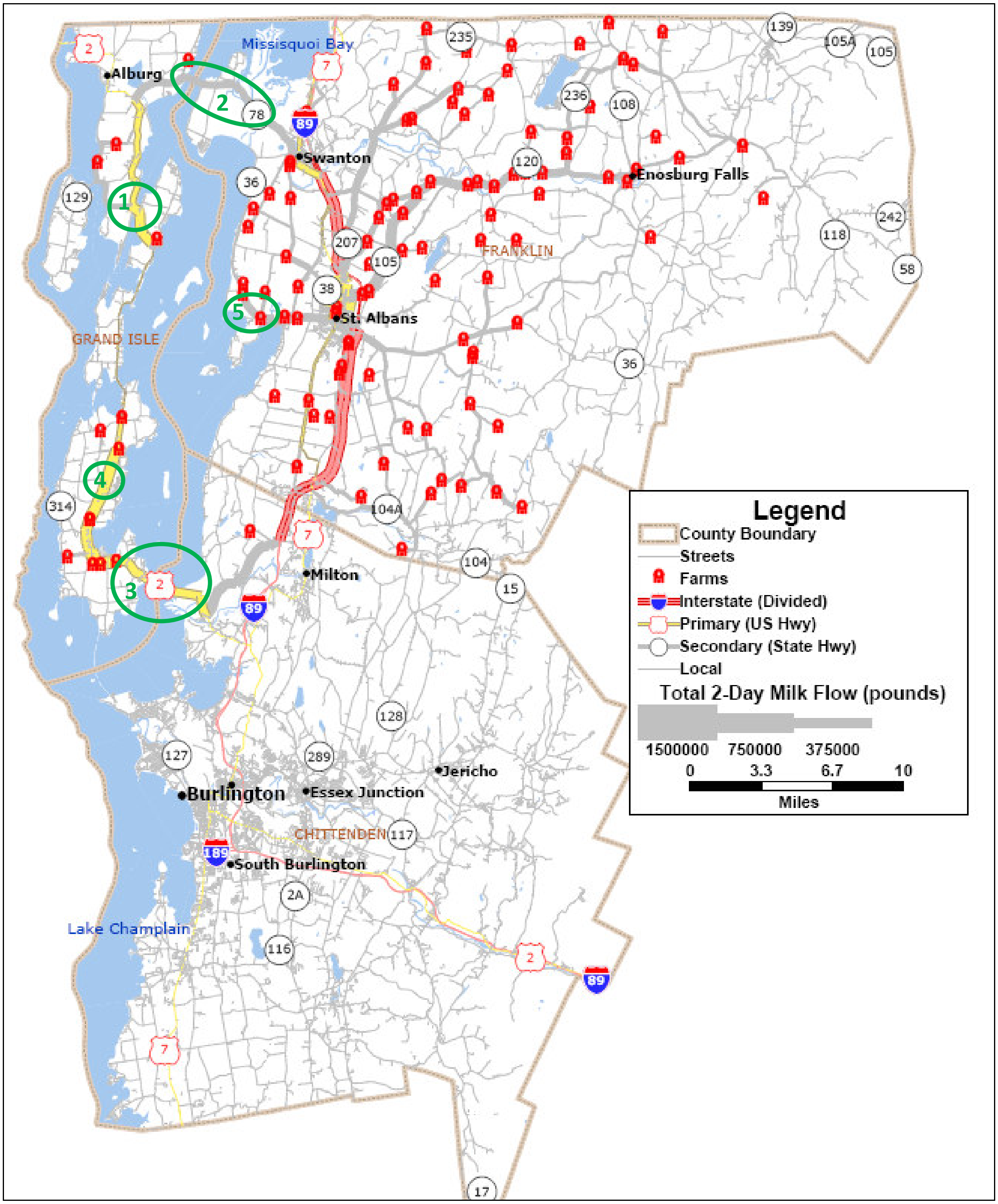

FIGURE 1 Total milk flows in northwest Vermont data set. Critical links indentified by the network robustness index have been circled. Numbers correspond to rankings in Table 2. This section of Vermont is bordered by Canada to the north and by New York to the west. Note: 1 mile = 1.61 km.

Network Robustness Index

The link-specific NRI was calculated as described in (*3*). First, the system-wide travel time (total vehicle hours traveled) when all links were present and operational in the network was calculated for the base scenario as:

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

where t_i is the travel time, x_i is the flow on link *i* at user equilibrium, and *I* is the set of all links in the network. Second, the system-wide travel time, c_a, after link *a* was removed and system traffic was re-assigned to a new equilibrium, was calculated similarly:

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

where $t_i^{(a)}$ is the new travel time and $x_i^{(a)}$ is the new flow on link *i* when link *a* has been removed. Finally, the NRI or travel time cost of losing link *a* was calculated as the increase in system-wide travel time over the baseline, as given by the following equation:

$$NRI_a = c_a - c$$

In this way, an NRI was calculated for each link in the network, and the links were ranked according to how critical they are to flow in the network. Links with higher NRIs are more critical. As applied to this data set, the NRI was calculated in terms of pound-hours. In other words, the loads of freight being carried were used as a weighting factor in the calculation of the NRI. Weights of milk loads are typically expressed in terms of pounds rather than tons. The use of a weight-time unit rather than weight-distance unit, such as ton-miles as is common parlance in freight transportation, captures potential differences in time to travel similar distances on alternate routes with different speed ratings as well as mileage differences.

RESULTS

Links with the highest values of NRI for the road network supporting the transport of milk from the 112 farms in the area of interest are identified in Figure 1 and listed in Table 2. Two of the top 3 most critical links are bridges connecting relatively isolated parts of the network into the main body of the network. None of these are isolating links as there are alternate routes back to the mainland (via the other bridge) for all trips. The links with the highest NRI values are not links with the greatest flow in the network. As

TABLE 2 Links with Highest Network Robustness Index, in Descending Order

Ranking	Description	Hourly Capacity (vph)[a]	Free-Flow Speed (mph)[b]	Total Flow (pounds)	NRI (pound-hours)
1	Crossing of Lake Champlain between South Alburg and North Hero Island	1,200	40	430,428	330,000
2	Extended crossing of the Missisquoi River, Charcoal Creek, and Lake Champlain between Swanton and Alburg	1,000	40	266,000	113,400
3	Crossing of Lake Champlain between West Milton and South Hero Island	1,200	40	387,000	106,000
4	Several segments of Route 2 on South Hero Island	1,200	40	462,600 to 584,600	30,000 to 50,000
5	Lake Road, west of Cherry Street in St. Albans Bay	1,000	40	390,300	25,000

[a]vph = vehicles per hour
[b]mph = miles per hour

shown in Figure 1, the greatest flows are leading to the St. Albans Cooperative Creamery near the center of St. Albans, the primary destination for milk collected in northwestern Vermont.

DISCUSSION

This study represents the first application of the NRI to freight transported in a real-world network, specifically the network of bulk milk collection in northwestern Vermont. Four of the 5 links with the highest NRI were associated with bridges, highlighting the importance of connectivity between portions of the network. The criticality of these links relative to total milk flows confirmed the utility of this index as an improved method of prioritizing links over simply looking at flow volume.

Two of the links identified as being critical according to their NRI (ranked 2 and 3) matched those that the authors had predicted would be critical based on their knowledge of the NRI procedure and a visual examination of the network. These include State Highway 78 that crosses several bodies of water between Swanton and Alburg and US Highway 2 that crosses Lake Champlain between West Milton and South Hero Island. Surprisingly, the link with the highest NRI is the US Highway 2 bridge between South Alburg and North Hero Island. In addition, the outputs identified 2 more critical links: State Route 36 between St. Albans Bay and St. Albans and another section of Highway 2 within the islands. These results were not predicted and show the value of the NRI procedure in identifying segments with limited connectivity as well as importance in terms of freight volumes.

In this application, the difference between the NRI for the bridges at the northern and southern ends of Grand Isle County is not large. This would not be predicted based on data for total commodity flows in Vermont which identify State Route 78 as an important truck route (15). The loss of either connector would result in over 100,000 pound-hours of delay to the overall milk transport network and represent a significant cost to the hauler. However, the combined effects of milk flow and time cost of re-routing over the US 2 bridge within the islands elevated this link to the top position. This ranking reflects inefficiency in milk routes in this area and assumes that the order of farm stops would be maintained if the link were lost, which would almost certainly not be the case. However, it does raise concerns over infrastructure maintenance given the current loads crossing this link every 2 days.

Although most of the heavy flows are concentrated in downtown St. Albans, the NRI results show that, because alternate routes exist for these streets, they are not critical. Several streets carry over 1.5 million pounds (over 174,000 gallons) every 2 days. It was beyond the scope of this analysis to confirm whether the alternate routes available can handle heavy truck traffic. On the other hand, the links connecting the network of interest with the northern and southern ends of Grand Isle County have limited alternate routes (each other), and carry 266,000 and 387,000 lbs of milk every 2 days. Thus, these roadways are far more critical to the robustness of milk transportation in northwestern Vermont.

Treatment of isolating links

An isolating link is a unique link between 2 otherwise unconnected networks, i.e., there is only 1 road leading into (or out of) a distinct road sub-network as described by (*20, 21*). Isolating links were handled in this application of the NRI in 2 ways: (1) by mapping farms to nearest intersection nodes on the network whenever possible and (2) by removing origins and destinations external to the network under study. In reality, farm driveways are isolating links, but it is expected that the disruption status of these links would be evident to milk haulers before a trip was initiated, and that the trip could be postponed or cancelled if disruptions of these links occurred. Therefore, their exclusion from the study is justified. In a traditional application of the NRI, centroid connectors, which are dummy links added to the network to bring centroid demand onto the actual road network, are often excluded from the analysis since they are an abstraction of a real roadway. Therefore, it is not unusual to exclude links at the beginning or the end of a trip in an NRI analysis. Removing data for routes crossing the border between Vermont and New York potentially decreased the NRI of critical links within the network of interest as those loads were not included. The region of the study was confined to northwestern Vermont because the intended audiences are the state's transportation planning agencies. However, the volume of the loads that crossed state boundaries could be included in future analyses. A better understanding of how much milk crosses state borders could be of interest for contingency planning aside from identifying critical infrastructure.

User-equilibrium assignment and avoidance of congestion

It is assumed that drivers would take the shortest-time paths between farms on their assigned routes. The TransCAD implementation of the NRI performs user-equilibrium assignment (*19*) to express the dynamics of capacity-restrained route selection. This traffic assignment model can account for congestion, but as applied to milk flows in Vermont, congestion was assumed to be non-existent. This assumption was supported by comments on driver surveys, which asserted that congestion was negligible. Two modifications were introduced to allow calculation of the NRI without congestion effects while still employing user-equilibrium assignment. First, the road capacities were set equal to a maximum capacity if all vehicles travelling were fully-loaded trucks carrying 60,000 lbs of milk. Second, a 2-day travel analysis period was used instead of a peak-hour period. Using a longer analysis period reduces the influence of congestion on links, even when vehicle flows are measured, since flows are averaged out over hours of the day when travel is at or below maximum free-flowing volumes. Obviously, the capacities used are not realistic, since there is a reasonable limit to how many large trucks can be travelling on a road at once (private motor vehicles tend to dominate most traffic flows) and it is unlikely that milk transport could be coordinated well enough to ensure that all trucks are fully-loaded at all times. However, these large capacities ensured that modeled traffic for the NRI would be free-flowing. The results of the traffic assignment confirmed that none of the volume to capacity ratios in the data set were higher than 0.0001.

Congestion effects had to be avoided in the application of the NRI procedure to milk transport, so it was not possible to use a capacity-disruption level other than 100%. It has been shown that the use of capacity-disruption levels other than 100% is effective at assessing the NRI for networks with isolating links (*20*). However, this modification to the NRI procedure relies on the effective assessment of congested travel times since links are being “choked” instead of being completely shut off. Therefore, this procedure could not be applied to modeling of milk transport with this dataset. The avoidance of congested travel in this NRI application is not expected to significantly affect the quality of the results. The portion of Vermont included in this study is almost entirely rural, and travel volumes are relatively low, and road connectivity is fairly good. Thus, it is unlikely that congested travel routinely affects milk transport in the study area.

Utility of NRI rankings

The NRI was proposed to identify and prioritize highway improvement projects (*3*). Protection of a link’s capacity can take many forms – from routine maintenance procedures, like pavement repair and snowplowing, to more comprehensive measures, like protection from floods or storm damage. Thus, the usefulness of the NRI extends from assisting with prioritizing routine maintenance to prioritizing recovery from catastrophic events such as a major flood [e.g., the flood of 1927 in Vermont that took out over 1200 bridges (*22*)].

The NRI ranking could facilitate investment in more critical road segments and increase the resilience of the food system in addition to benefiting commuters and business travelers. While links carrying the highest flow, such as those immediately leading to the primary destination in St. Albans, are important to the dairy industry, the presence of alternate routes makes these less critical. The links identified as critical by the NRI are not only important to the dairy industry but are of broader importance to the state for carrying other freight and commuter traffic. Thus, in addition to providing the state with useful information for the protection of the dairy industry, the ranking provides the dairy industry with useful information with which to lobby the state regarding infrastructure protection and improvement.

Future directions

This paper presents the results of analysis of milk flows on only a small section of the Vermont road network. With good data, the NRI could be calculated for networks carrying any other type or combination of freight or other traffic. The authors plan to extend the NRI analysis to milk flows in the entire state. This extension will allow consideration of critical links supporting milk transport when prioritizing improvement projects on highways statewide. Recognizing that the milk flows are of vital importance to Vermont's economy, it would be helpful to adopt the NRI as the preferred method of prioritizing links for maintenance, improvement, and protection. The authors also intend to re-introduce normal automotive traffic on this road network along with the analysis of freight flow with the NRI. This step will require the development of a generalized cost of delay, equating lost time for drivers and passengers with delayed delivery of commodities like milk. Once these delays are translated into generalized costs, the NRI can be used to assess the most critical links in the network considering the milk industry and the needs of commuters and other travelers.

CONCLUSIONS

In this analysis of milk flows in northwestern Vermont, links identified as critical by the NRI were not the links carrying the greatest flows. Although commuter and business traffic flows were ignored in this analysis, the authors would argue for the inclusion of common freight flows when assessing the criticality of infrastructure and prioritizing improvements. Of perhaps greater importance for state infrastructure project prioritization is a better understanding of the flows of truck traffic over town highways and roads. For instance, the transport of agricultural and food products benefits the state economy and consumers, so infrastructure investments at the local level to support this traffic would have benefits beyond the local community. Town road planners, therefore, would have an interest in the NRI for links within their town and these links also would be of value to supporting the local food system statewide. Milk haulers, cooperatives, and processors could use NRI values to assist in supply chain risk management and business continuity planning.

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