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OPTIMIZATION OF SNOW REMOVAL IN VERMONT

Report 2013 – 12

August 2013

OPTIMIZATION OF SNOW REMOVAL IN VERMONT

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August, 2013

Reporting on SPR-RAC-727

STATE OF VERMONT
AGENCY OF TRANSPORTATION

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16. Abstract

The purpose of this report is to document the research activities performed under project SPR-RAC-727 for the State of Vermont, Agency of Transportation, Materials & Research Section entitled “Optimization of Snow Removal in Vermont”. The overall objective for this project was to develop, for VTrans roadway snow and ice control operations, storm-specific routes designed to maximize the efficiency of the service provided in terms of labor-hours and fuel. This report describes the set of processes implemented for optimizing RSIC operations for the roadways that VTrans is responsible for. Three different approaches to establishing priority for certain roadways are implemented, including one that uses the Network Robustness Index developed previously by researchers at the UVM TRC, and each is run for three storm levels – low-salt, medium-salt, and high-salt. Storm-intensity levels are important because they dictate the amount of salt application required - – 200 lbs/mile, 500 lbs/mile, and 800 lbs/mile, which is the primary constraint for the maximum length of a round-trip route for roadway snow and ice control.

The first task was to optimize the service areas for each of the 61 VTrans maintenance garages based on the travel time between each garage and the surrounding road network. The second task was to develop alternative vehicle allocation methods and assign each of the vehicles in the VTrans RSIC fleet to the maintenance garages based on these methods. The third task was to optimally route each of these vehicle allocations according to the combined service time/fuel consumption metric. The fourth and final task was to evaluate the competing vehicle allocations based on the speed with which high priority road corridors are serviced.

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Executive Summary

The purpose of this report is to document the research activities performed under project SPR-RAC-727 for the State of Vermont, Agency of Transportation, Materials & Research Section entitled “Optimization of Snow Removal in Vermont”. The overall objective for this project was to develop, for VTrans roadway snow and ice control operations, storm-specific routes designed to maximize the efficiency of the service provided in terms of labor-hours and fuel. This report describes the set of processes implemented for optimizing RSIC operations for the roadways that VTrans is responsible for. Three different approaches to establishing priority for certain roadways are implemented, including one that uses the Network Robustness Index developed previously by researchers at the UVM TRC, and each is run for three storm levels – low-salt, medium-salt, and high-salt. Storm-intensity levels are important because they dictate the amount of salt application required - – 200 lbs/mile, 500 lbs/mile, and 800 lbs/mile, which is the primary constraint for the maximum length of a round-trip route for roadway snow and ice control.

The first task was to optimize the service areas for each of the 61 VTrans maintenance garages based on the travel time between each garage and the surrounding road network. The second task was to develop alternative vehicle allocation methods and assign each of the vehicles in the VTrans RSIC fleet to the maintenance garages based on these methods. The third task was to optimally route each of these vehicle allocations according to the combined service time/fuel consumption metric. The fourth and final task was to evaluate the competing vehicle allocations based on the speed with which high priority road corridors are serviced.

The specific methods used to solve the three optimization problems required to complete these tasks are:

- Defining and determining optimal service territories
- Defining and determining optimal vehicle allocations
- Optimal vehicle routing

Specific adjustments to these methods were necessary for the Vermont application. Each optimization was performed for each of three different approaches to roadway priority, and for each storm-intensity level, for a total of nine (9) solutions. One additional solution provides the maximum number of trucks for each garage to reach “saturation”, or the point where additional vehicles do not lead to significant gains in efficiency.

To complete the fourth task, the individual garage-level allocations were compared using the absolute percent error and the total statewide allocations (for all 61 garages) were compared using the mean absolute normalized error. The 10 sets of vehicle routes were compared using the total vehicle-hours of travel for all RSIC vehicles to cover the entire system of roadways the state is responsible for, the duration of the longest single route, the average route length, the time required to service all of the roadways in the network, and the time required to service 90% of the most critical links in the network.

An analysis of the service-territory assignments that result from assigning each link in the road network to the nearest garage reveals the disparities that result. The variety of the lengths of the longest round-trips between garages is an indication of how inequitable the service territories are. The longest round-trip from a garage, 95 minutes, occurs in the Colchester garage service territory; whereas the average longest round-trip travel time is

64 minutes. The Colchester garage is also the location of the service territory with the longest total road length (146 miles), the highest level of road criticality (11,402 mile-hours per day), and the most Priority 1 roadways (106 miles). These disparities indicate that a different number of trucks are required at each garage to effectively service its territory.

Consequently, the allocation procedures resulted in differences between the garages. The minimum number of trucks assigned to a garage was 1 for the storm-intensity simulations, and 2 for the saturation scenario. The maximum number of tricks assigned to a garage ranged from 10 to 16 trucks, depending on the storm intensity and the approach to measuring priority. For all of the approaches, the maximum allocation of trucks occurred for the Colchester garage. For the unlimited approach, a total of 317 trucks were allocated to saturate all 61 garages and several garages were provided with 10 trucks (including Colchester).

As measured by the mean absolute normalized error, the best fit to the existing allocation, on average, came from the Road Length approach, which did not include any "weighting" of roadways according to their priority level of modeled level of criticality. This result is not surprising, since the most intuitive allocation would likely be one based on total roadway miles. Any consideration of priority of criticality would require a level of modeling that is not known to have been done previously for RSIC route planning.

The performance metrics for each of the 10 RSIC route systems generated for this project are summarized in Table 1.

Table 1 Performance Metrics for each of the 10 RISC Route Systems

Allocation Approach / Storm-Intensity	90% NRI[1] (hrs)	Total VHTs	Longest Route[2] (hrs)	No. of Unused Vehicles [3]	Average Route Length (hrs)	Final Service Time[4] (hrs)
Low-Salt Scenario (200 lbs per mile)						
Roadway Length	1.37	281	2.1	4	1.15	2.1
Roadway Length ÷ Priority	1.36	282	1.7	0	1.13	1.7
Roadway NRI	1.36	280	1.9	6	1.15	1.9
Medium-Salt Scenario (500 lbs per mile)						
Roadway Length	1.29	282	2.5	9	1.18	2.5
Roadway Length ÷ Priority	1.24	286	1.8	5	1.17	1.8
Roadway NRI	1.26	280	2.0	8	1.16	2.0
High-Salt Scenario (800 lbs per mile)						
Roadway Length	2.04	298	2.3	6	1.23	4.3
Roadway Length ÷ Priority	1.52	306	2.5	7	1.26	4.0
Roadway NRI	0.99	304	2.7	0	1.22	2.8
Unlimited (317 Trucks)	1.28	299	1.6	0	1.20	1.6

An initial observation of the results is that the relationship between the salt requirements of the storm and the total VHTs required to provide RSIC services statewide are not linear. The requirements for the low- and medium-salt storms are both relatively easy to meet with the existing fleet without the need to return to a garage to re-supply. However, for the high-salt storm, existing vehicle capacities become relatively constrained, and a few second passes are required, as evidenced by the difference between the longest single route and the final service time for the “Roadway Length” and “Roadway Length ÷ Priority” approaches. For the high-salt scenario, the remarkable efficiency yielded by the approach simulating an “Unlimited” supply of vehicles is further evidence of the constraints placed on the existing vehicle fleet when large quantities of salt are required. The best use of the route system created by the “Unlimited” scenario is to guide the need for “shifting” vehicles from one part of the state to another in the event of a predictably regional storm event.

All of the results must be considered in the context of the number of unused vehicles left after the routing system was completed. It is likely that “Roadway NRI” approach for the medium-salt scenario was adversely affected by the 8 unused vehicles. Evidence for this finding can be found in the reduced number of VHTs taken by that approach (280, as opposed to 286 for the “Roadway Length ÷ Priority” approach), and the longer final service time (2.0 hours, as opposed to 1.8 hours for the “Roadway Length ÷ Priority” approach). These differences also provide evidence of the competing needs for each optimized route system to minimize VHTs and total service time. For most of the approach/scenario combinations, approach with the shortest final service time also incurred the largest number of VHTs. Therefore, more fuel is generally needed to complete the entire network faster.

However, this relationship does not hold for the time taken to provide service to 90% of the critical links in the network. For the allocations based on “Roadway NRI”, the most optimal balance between service and fuel efficiency was reached. In every case, the “Roadway NRI” approach appeared to yield a route system with the best balance of fuel efficiency, speed to final service time, especially for the high-salt scenario, where capacity of the vehicles was most constrained. In fact, the “Roadway NRI” approach for the high-salt scenario was the only one (aside from the “Unlimited” approach) that did not require a second pass of any RSIC vehicle in the state, using every vehicle efficiently and effectively. With these considerations in mind, the Roadway NRI route systems appear to be the most effective, and are recommended for primary use in evaluating the existing allocations and route systems.

The RSIC activities that VTrans undertakes in response to a given winter weather event depends upon a number of dynamic factors that cannot be fully accounted for in a finite number of modeling runs. These factors include storm duration, geographically variable storm-intensity and human factors such as traffic accidents, which can radically alter the RSIC services. Accordingly, any static set of vehicle route system will best serve as a starting point for an evaluation of RSIC operations and may have to be modified according the knowledge and expertise of the VTrans Operations staff.

The routes generated by this process are designed to service all road segments once. For many storms, the same road segment is likely to require multiple “passes” to reach performance goals for bare pavement. Since the routes presented here all return to their original garage, these routes can be repeated as many times as necessary of the course of a storm. However, the most optimal routing for repeated road coverage may not be identical to the routing required to cover all road segments once.

In spite of these limitations, this report provides several concrete items of information that can inform future RSIC operations in Vermont. The garage service-territory assignments provide the basis for a re-evaluation of the current district-based system. The unlimited vehicle-allocation provides information on the maximum saturation point for RSIC routing, which could be useful to consider shifting vehicles from one region of the state where a storm may not have reached, to another region which might be getting hit particularly hard by the same storm. Finally, the routes themselves provide a starting point for evaluating existing routes. Substantial deviations between the modeled routes and the current routes should be examined to see if they result from known limitations in the modeling process or from apparent inefficiencies in the existing routes.

1 Introduction

1.1 Background

In the winter of 2011, record snowfall caused Vermont to exceed the total 2010 winter road maintenance budget by nearly 50% before the final storm of the season in March (Bullard, 2011). That storm disabled many of the roadways in the state, and several bus transit agencies had to temporarily suspend service on some routes.

The events of winter 2011 illustrate two, sometimes contradictory, challenges facing the Operations Division of the Vermont Agency of Transportation (VTrans) in executing roadway snow and ice control (RSIC) operations. First and foremost, RSIC activities must return roadways to safe operating conditions as quickly as possible after a winter storm event. As recognized in the Agency's Snow and Ice Control Plan, priority must be given to those highway corridors that are determined to be critical to the functioning of the transportation network (VTrans, 2009). The efficient return of capacity to snow-covered roads provides immediate benefits to the Vermont economy, as impedances to critical business, freight, and emergency traffic flow are removed.

Second, these operations must be carried out as cost efficiently as possible. Maintaining winter travel is the highest-profile activity of VTrans (VTrans, 2011a) and consumes more than 10% of the Agency's annual budget. RSIC operations, therefore, must be planned and carried out in a manner that restores its roadway capacity with the lowest possible expenditure of fuel and labor-hours.

While these objectives can be contradictory, RSIC operations can be optimized to improve performance from both perspectives. Returning roadways to safe operating conditions can be optimized by implementing comprehensive performance measures for RSCI operations. These performance measures can be short-term, providing immediate feedback on the effectiveness of the link-specific operation so that intra-storm adjustments can be made, and long-term, providing a "grade" for the effectiveness of the network-wide RSIC operations so that inter-storm adjustments can be made. While the development and implementation of comprehensive performance measures for winter storm events is the goal of a future project, the goal of this project involves carrying out the RSIC operations in the most cost-effective way, minimizing fuel and labor expenditures to clear the entire state roadway network.

Optimizing RSIC operations to minimize cost includes three distinct problems: a network-clustering problem, a vehicle allocation problem, and a vehicle routing problem. Each of these problems needs to be addressed before the next can be solved. First, service territories must be determined so that each garage has a set of roadway segments that it is responsible for. Next, the available RSIC vehicles must be assigned to garages based on the size and characteristics of their service territories. Finally, a route must be developed for each RSIC vehicle at each garage so that the collective system of routes minimizes total vehicle-hours of travel on the network.

Deriving optimal routes for statewide RSIC operations involves a complex balancing of solutions to these three problems. Larger service territories require more trucks if overall travel times are to be minimized, and dedicating more trucks to one garage sacrifices the time it takes to complete RSIC operations in another garage since the number of trucks available to each garage is proportional to the time it takes to clear all of its roads. RSIC operations are often guided by principles of priority – certain groups of roadways are frequently considered to have a higher priority than others (Campbell and Langevin, 2000; Korteweg and Volgenant. 2006; Perrier et. al., 2006).

These principles of priority guide the way service territories and vehicles are allocated to each garage, so that the efficient routes developed for each garage also address the most critical links in the network first. The current RSIC Operations Plan for VTrans establishes three levels of service for three categories of roadway links (VTrans, 2009).

1.2 Project Description

In this project, the concept of priority is extended further by introducing a continuous measure of roadway criticality, the Network Robustness Index (NRI). The NRI has been demonstrated by Scott et al., (2006) and in a refined form by Sullivan et al., (2010) to outperform localized measures of roadway criticality such as the v/c ratio and the annual average daily traffic (AADT).

The overall objective for this project was to develop, for VTrans RSIC operations, storm-specific routes designed to maximize the efficiency of the service provided in terms of labor-hours and fuel. This report describes the set of processes implemented for optimizing RSIC operations for the roadways that VTrans is responsible for.. Three different approaches to establishing priority for certain roadways are implemented, including one that uses the NRI, and each is run for three storm levels – low-salt, medium-salt, and high-salt. Storm-intensity levels are important because they dictate the amount of salt application required - – 200 lbs/mile, 500 lbs/mile, and 800 lbs/mile, which is the primary constraint for the maximum length of a round-trip RSIC route.

The first task was to optimize the service areas for each of the 61 VTrans maintenance garages based on the travel time between each garage and the surrounding road network. The second task was to develop alternative vehicle allocation methods and assign each of the vehicles in the VTrans RSIC fleet to the maintenance garages based on these methods. The third task was to optimally route each of these vehicle allocations according to the combined service time/fuel consumption metric. The fourth and final task was to evaluate the competing vehicle allocations based on the speed with which high priority road corridors, as measured by the network robustness index (NRI), are serviced.

1.3 Report Organization

Section 2 contains an exhaustive description of the methodology used in this project, including how optimal service territories, vehicle allocations and vehicle routes were defined. Section 3 contains a description of the data sources used for this project and how the raw data were prepared for use in the vehicle-routing model. Section 4 presents the results of the study, and a comparison of the vehicle allocation and routing processes to VTrans' existing allocation and routing systems. Section 4.4 discusses how to integrate the findings from this project into RSIC practice.

2 Methodology

In this section, general information on the class of solution methods available in this field of research is provided. The specific methods used to solve the three optimization problems are described in greater detail:

- Defining and determining optimal service territories
- Defining and determining optimal vehicle allocations
- Optimal vehicle routing

Additional specific adjustments to these methods that were necessary for the Vermont application are also described.

2.1 Defining and Determining Optimal Service Territories

In this project, a garage's service territory was considered optimal when it included all road links closer to it than to any other garage. Anytime that a road link was inadvertently assigned to the service territory of a garage other than its closest garage, it was reassigned to reduce the minimum elapsed time from a simultaneous start in which the entire system can be serviced.

Figure 1 illustrates, on a simple network, the potential savings in elapsed time from a simultaneous start achieved by optimally aligning garage service territories.

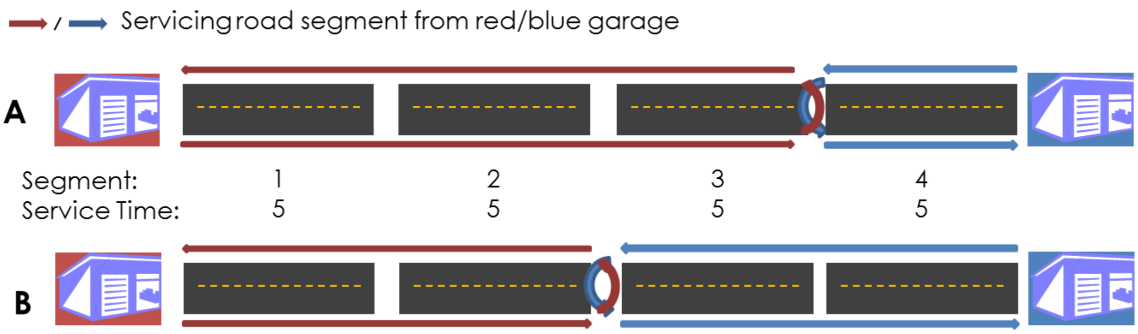

Figure 1 Service Territory Optimization

In Figure 1A, segment 3 was inadvertently assigned to the left garage. By reassigning it to the garage on the right, as in Figure 1B, the elapsed time required to service all segments in the network from a simultaneous start (which is equivalent to the time required to service the longest route) is reduced from 30 minutes to 20 minutes. In some circumstances, misaligned service territories can also result in deadheading as a vehicle from one garage crosses the service territory of another garage before beginning RSIC activities. In these cases, service territory misalignment increases the cost as well as the time associated with RSIC operations.

Proximity of each roadway link was measured in terms of the travel time required to go from the garage to the midpoint of the link. For this project, a midpoint "stop" was created for each travel direction of every link in the network that VTrans is responsible for maintaining. These "stops" also facilitated the vehicle routing procedure, as explained below. After running the shortest path function in TransCAD, links were assigned to the garage that produced the fastest shortest path to its "stop".

Because RSIC vehicles are constrained in where they can safely turnaround and the TransCAD function does not measure the round-trip shortest path, the shortest path for stops on opposite sides of the same road segment originated occasionally from different garages. As shown in Figure 2A, counter-productive service-territory assignments at the boundary between the service territories of adjacent garages will result and the amount of deadheading and the total vehicle-hours of travel (VHTs) required to service all links will be increased. Since it is unlikely that the RSIC vehicles will arrive at the boundary segment at the same time, the first vehicle will arrive to service the road in one direction and then deadhead across the same segment in the opposite direction even though that direction has not yet been serviced. VHTs are considered a proxy for fuel used, so this service-territory assignment is not optimal. To avoid this situation, segments at the edge of each garage's service area were inspected and stops were reassigned to eliminate service-territory overlaps, as shown in Figure 2B.

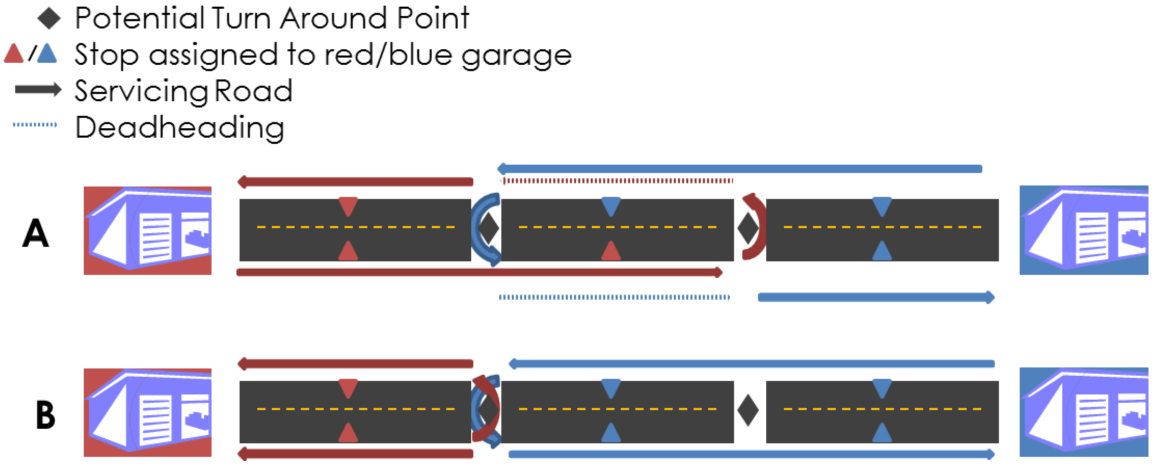

Figure 2 Manual alterations to the shortest path procedure. A) Stops automatically assigned to the closest garage based on travel time. B) Stops reassigned to eliminate overlapping routes.

2.2 Defining and Determining Optimal Vehicle Allocations

2.2.1 Defining Optimal Vehicle Allocation

The vehicle allocation for an individual garage is optimal when all vehicles at the garage are in use and when adding additional vehicles to the garage does not improve the service time for its territory. The optimal vehicle allocation for a garage depends on the reach and characteristics of the roadway links in its service territory as well as the range (in terms of salt or fuel) of the vehicles stationed there. Figure 3 shows three different vehicle-allocation levels for a simplified service territory. In Figure 3A, all road segments are serviced by a single vehicle. This vehicle allocation is non-optimal, or under-saturated, since adding a second vehicle to the garage and creating two separate routes, as in Figure 3B, reduces the time required to service the network by 50% if the travel time on all links is equal. At a certain point, however, adding additional vehicles to the garage will not improve the service time, but rather results in vehicles sitting idle, as is shown in Figure 3C.

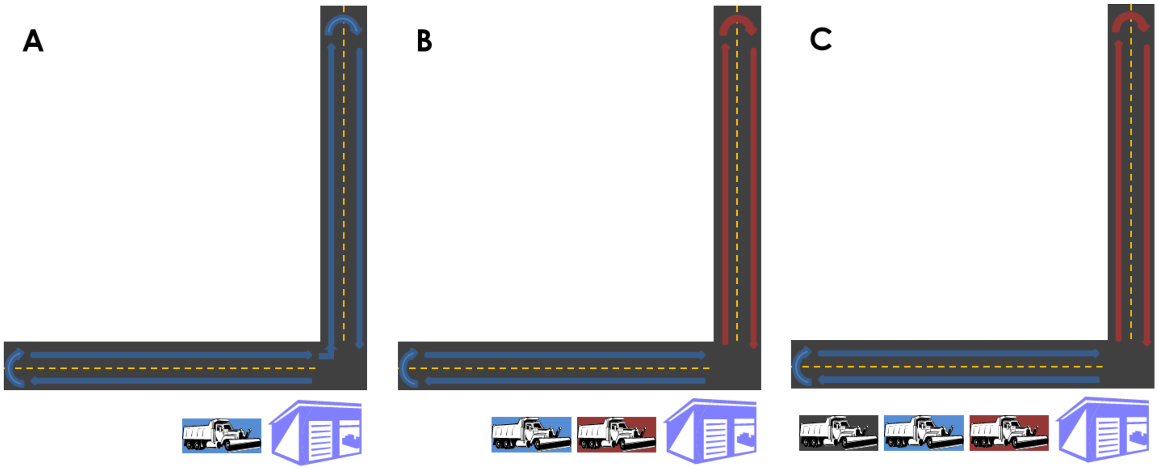

Figure 3 Route saturation levels. A) Unsaturated vehicle allocation; additional vehicles will reduce the time until all road segments are treated B) Saturated vehicle allocation; the time until all road segments are treated is minimized C) Over-saturated vehicle allocation; idle vehicle cannot be deployed in a manner that reduces the time until all roads are treated.

Because vehicles are not in use in Figure 3C, this allocation is over-saturated and non-optimal. In practice, an over-saturated vehicle allocation may be helpful during intense storms, as multiple vehicles could follow the same route at staggered intervals, servicing each road segment at more frequent intervals. Over-saturation may also be necessary where divided highways with multiple lanes are present, and both a right-lane plow and a left-lane plow are required for a single roadway segment.

Given the size of the current VTrans RSIC fleet, it is not possible to allocate an optimal number of vehicles to all garages. Any vehicle allocation will, therefore, leave some garages under-saturated. Therefore, a guiding approach to the vehicle-allocation procedure is required. As described previously, a common guiding approach in the literature is to service high-priority highways more rapidly by weighting the allocation toward those service territories where more high-priority roadways are included. In Figure 4, for example, Service Territory One has more high-priority road segments than Service Territory Two. If there are not enough vehicles to saturate both service areas, saturating Service Territory One, as in Figure 4A, becomes preferable. In order to assess the effectiveness of this type of allocation procedure, a metric must be used to measure the time required to service high-priority links. For the example shown in Figure 4, the time required to service the high-priority links is lower for the allocation shown in Figure 4A than it is for the allocation shown in Figure 4B, assuming that travel times on all links are equal.

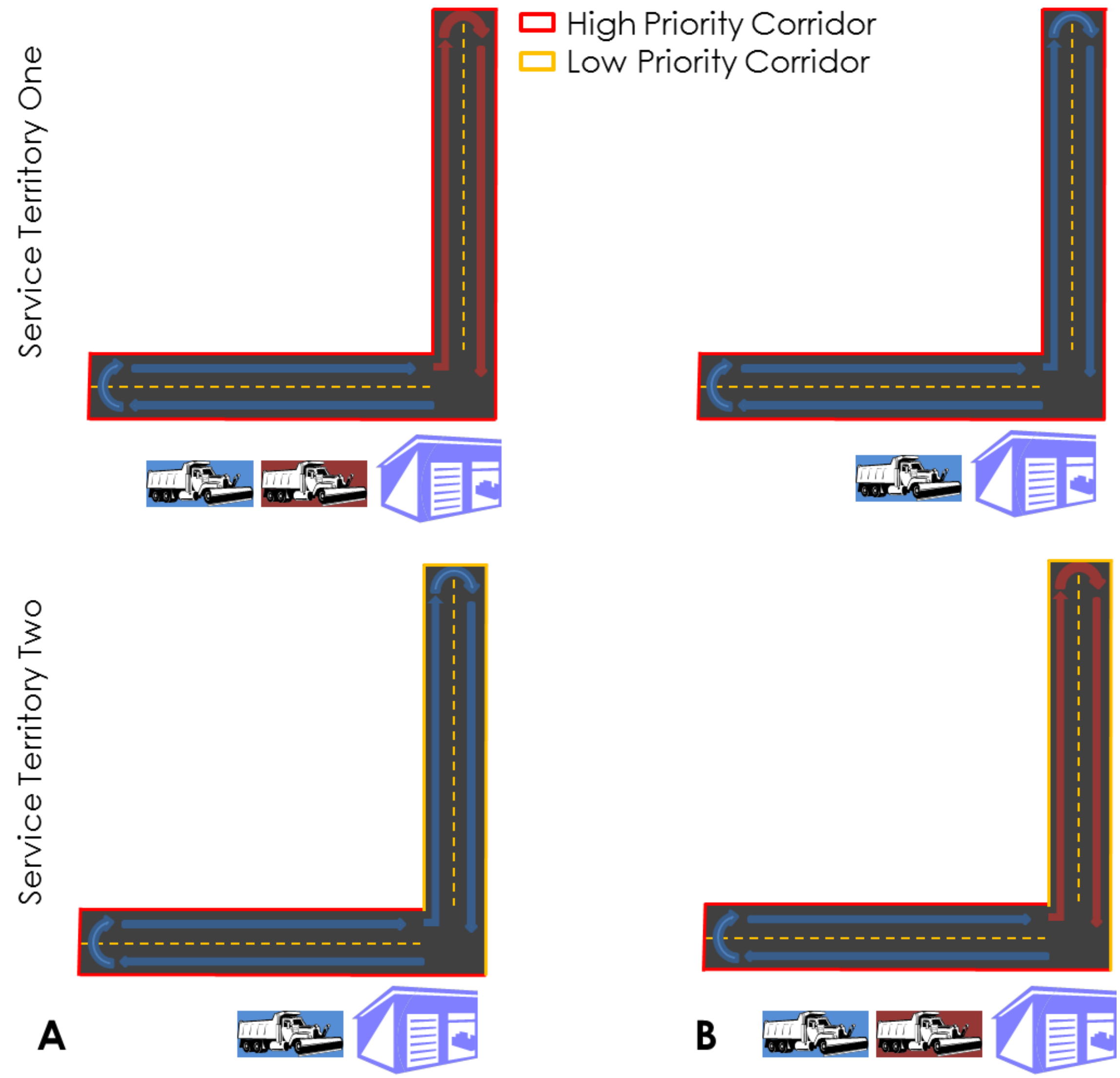

Figure 4 Optimizing Vehicle Allocations across Service Territories

2.2.2 Vehicle Allocation

Realizing that any vehicle allocation would result in unsaturated conditions, three different approaches to establishing priority were implemented, in increasing order of complexity. For each of the approaches, the storm-specific minimum number of trucks for each garage was determined such that all of the service territory could be covered in a single set of routes, without any vehicle needing to return to the garage for salt.

The first approach, a baseline approach, essentially treated all roadways with equal priority, allocating vehicles based solely on the total length of roadway within the service territory of garage *i* (L_i):

$$L_i = \sum_{q=1}^{r} l_q \tag{1}$$

where l_q is the length of link *q* and there are *r* links in the service territory of garage *i.*

Each garage's fraction of the total roadway length that the state is responsible for was then taken to be the fraction of the total number of trucks available for RSIC operations (249) allocated to it:

$$N_i = \text{Maximum}\,(249 \times \frac{L_i}{\sum_{i=1}^{n} L_i}, N_{min}^{ij}) \tag{2}$$

where N_i is the number of trucks allocated to garage *i*, L_i is the total roadway length in the service territory of garage *i*, *n* is the set of all 61 garages, and N^{ij}_{min} is the minimum number of trucks needed to service garage *i* at storm-intensity *j*. These minima are calculated as:

$$N_{min}^{ij} = \text{Maximum}\,(\frac{L_i \times R_j}{C_{max}}, 1) \tag{3}$$

where R_j is the salt application rate specific to storm-intensity *j* (200 lbs/mile, 500 lbs/mile, or 800 lbs/mile) and C_{max} is the maximum capacity of any truck in the fleet, in pounds.

The second approach used the three priority classifications in VTrans' Snow and Ice Control Plan (VTrans, 2009). To quantify the three priority levels, the length of each roadway was adjusted by dividing it by the priority level – 1, 2, or 3. For links with priority level 2 or 3, this adjustment reduces the effective length of link *q* by its priority level *p*:

$$L_i = \sum_{q=1}^{r} \frac{l_q}{p_q} \tag{4}$$

where *p* can be either 1, 2, or 3.

The effective lengths L_i were then summed for each garage and this new sum was used to calculate the garage's revised fraction of the total number of trucks to be allocated to it, as shown in Equation 2.

The third approach used the continuous priority-classification provided by the NRI for each roadway link in the network VTrans is responsible for maintaining. The NRI takes advantage of the Vermont Travel Model to calculate the criticality of each link in the state under various disruptive situations. The Vermont Travel Model is a tool for simulating a typical day of travel in Vermont, allowing users to alter the structure and capacity of the network to see how travelers will respond (Sullivan and Conger, 2012). To calculate the NRI, first the total statewide VHTs for the typical day of travel are determined. Then each link in the network is disrupted as a capacity-reduction, travelers are re-routed in response to the disruption, and the NRI of that link is measured as the change in VHTs statewide that occur following the disruption. This procedure is repeated for every link the Agency is responsible for, and the relative position of each link in a ranked list of NRIs provides an indication of how critical that link is to the entire network.

Three different sets of NRIs were used, one for each of the storm levels being considered. A light storm corresponded to an NRI simulating a 25% loss of capacity; a medium storm corresponded to an NRI with a 50% loss of capacity; and a heavy storm corresponded to an NRI with a 75% loss of capacity. In each case, the length of each roadway was adjusted by multiplying it by its NRI:

$$L_i = \sum_{q=1}^{r} NRI_q \times l_q \tag{5}$$

where *NRI* ranges from -9 to 1,689. NRI values of less than 0, although, counter-intuitive, are possible when the disruption of a given link actual decreases the total VHT on the network. This uncommon occurrence is referred to as Braess' Paradox, and can be attributed to the presence of a high-capacity link which is not frequently used, with a redundant low-capacity link which provides an alternate route for travelers (Sullivan et. al., 2010).

This adjustment increased the effective lengths of critical links, and diminished effective lengths of non-critical links to 0 or less than 0. These effective lengths were then summed for each garage and this new sum was used to calculate the garage's revised fraction of the total number of trucks to be allocated to it, as shown in Equation 2.

For all of the approaches, it was possible for a final total truck allocation of greater than 249 to result due to the indiscriminant use of the minimum requirement. Therefore, once the initial allocation was completed, additional iterations were necessary to redistribute the excess vehicles. Excess vehicle were redistributed according to their effective length, as found in Equation 4.

Once an appropriate number of trucks was found for each approach for each of the three storm levels, the next step was to allocate the actual trucks from the Vermont fleet, which is described in Table 2.

Table 2 VTrans RSIC Vehicle Fleet

Make	Model	Model Year(s)	Body Volume for Salt (cy)	No. of Trucks
International	2574	2001-2002	14.4	5
International	7600	2003, 2005, 2008, 2010-2012	14.4	74
International	7600 6x4	2009	7.8	3
International	7400	2002-2003, 2005-2006, 2010, 2012	7.5	88
International	7500	2005-2008	7.5	69
International	4700	2001	2.5	3
International	4900	2002	2.5	2
International	7300	2005-2006	2.5	4
International	4400	2007	2.5	1

VTrans also owns a fleet of pickup trucks, some of which have plows on them. However, these were assumed to be specialized vehicles for plowing smaller areas, like garage parking lots. Thus, they were not included in the allocation. The list described in Table 1 also does not include dedicated left-lane plows, which are used in tandem on divided highways and interstates to simultaneously plow both the right and left lanes.

The allocation proceeded in "rounds" with the smallest trucks (2.5 cy capacity) distributed individually to the garage(s) with the highest demand. As a garage received a truck, its demand was reduced by 1. Each "round" of allocations consisted of the distribution of the smallest available trucks to the garage(s) with the highest current demand. This process continued until all of the trucks had been distributed and all of the demand had been met. Since the largest trucks were distributed last, every garage received at least one 14.4-cy truck.

The allocation rounds proceeded from smallest trucks to largest trucks for two reasons. The first reason was to ensure that garages that had been scheduled to receive only one truck got the largest available truck, since that size had been used to calculate N^{ij}_{min}. The second reason was that most of the garages with the highest demand for trucks appeared to be in areas with greater urban density. This increased density means more connectivity, shorter roadway lengths, and more urbanized conditions, where a smaller truck should prove more useful.

The result of this process was a series of 9 distinct vehicle allocations, with a truck table describing the type and number of trucks at each garage.

2.2.3 Assignment of Second Passes and Unused Vehicles

After each of the approaches were implemented and truck tables had been created, the total salt capacity of the trucks assigned to each garage was compared to the total salt required to treat the service territory of that garage. If a garage lacked sufficient capacity to service all of the road segments in its service territory, vehicles assigned to that depot were duplicated, creating a set of "ghost" vehicles, representing the capability of each vehicle to traverse a second route after finishing its initial route. Generally, the lowest capacity vehicles were duplicated first, since they would have had the shortest routes and, therefore, should be the first vehicles back to the garage and available to start a subsequent route.

Several vehicle allocations resulted in over-saturated vehicle assignments at a subset of garages. Over-saturation was discovered after the vehicle-routing process had been completed, and unused vehicles were apparent because the number of routes created for a given garage was smaller than the number of vehicles assigned to that garage. If 10 or more vehicles remained unused after the routing process was completed, these unused vehicles were reallocated to other garages. Unused vehicles were reallocated first to garages with "ghost" vehicles and then to the garages with the longest service times.

Each time a vehicle was assigned to a garage, it was assumed to reduce the time required to service that territory in proportion to the number of vehicles assigned to that garage. Thus, if a garage that was allocated initially two vehicles was assigned a third vehicle during the reallocation process, it was assumed that the time required to service its territory would decrease by 50%. This assumption allowed all vehicles to be reallocated prior to repeating the vehicle routing process. Once all vehicles were reallocated, the vehicle routing process was repeated. This re-assignment was performed once, so some vehicles were left unused at a subset of garages.

2.3 Optimal Vehicle Routing

2.3.1 Defining Optimal Vehicle Routing

The operations research field has explored a number of approaches for creating efficient routes for service vehicles (Golden and Wong 1981; Perrier, Langevin et al. 2006; Perrier, Langevin et al. 2007; Pisinger and Ropke 2007; Perrier, Langevin et al. 2008; Salazar-Aguilar, Langevin et al. 2011). These methods have been developed considering a variety of applications including package delivery, RSIC services and garbage collection. Generally, this class of methods are known as vehicle-routing problems, and they are characterized using one of two related mathematical formulations, either arc-routing or vehicle-routing. Arc routing problems require that service vehicles traverse a specified set of network links, while vehicle-routing problems require the vehicle to stop at a specified set of points, but do not inherently require that the vehicles traverse specific road segments. Both of these problems are mathematically complex and time-consuming to solve exactly on complex networks, such as the Vermont road network, and a number of heuristics methods have been developed to help. TransCAD includes automated solutions to both the arc-routing and vehicle-routing problems.

While the RSIC routing problem initially resembles an arc-routing problem, in that treatment must be applied to entire road segments rather than at individual stops, there are a number of shortcomings in the way that the arc-routing problem is implemented in TransCAD that limited its value for this application. First, TransCAD's arc-routing function has extremely limited capability to represent specific vehicle-capacity constraints. Specifically, all vehicles routed from a given home depot (garage, in our case) must have the same capacity (for salt, in our case) making them an inadequate representation of the Vermont RSIC fleet, which has vehicles whose salt capacities range from 2.5 to 14.4 cubic yards. In addition, for each garage, the arc-routing function outputs a single continuous route that covers all road segments assigned to the garage rather than a set of individual routes for each vehicle from, and back to, that garage. TransCAD has the ability to break this single route into vehicle-specific shifts during post processing but these shifts do not account for travel from the garage to the point where the vehicle begins providing service. Consequently, using the arc-routing problem would require considerable manual processing to produce and evaluate specific vehicle-routes.

Fortunately, the arc-routing problem is transformed into a vehicle-routing problem by introducing "stops" along each road segment in such a manner that all road segments be completely traversed by the service vehicles in the process of serving these stops (Longo, de Aragão et al. 2006). "Stops" in this framework are locations of demand, where a certain product or products are required, as in the distribution of retail products from a central warehouse to satellite retail locations. In our conceptualization, though, each "stop" is the mid-point of the roadway segment, and has a "demand" for salt based on the length of the segment. When each "stop" is serviced, the vehicle's salt load is reduced by the amount of salt required to cover the segment. In this way, the traditional conceptualization of warehouse / satellite retail is translated for the RSIC application. The salt ""demand" for each roadway segment is based on the intensity of the storm expected – high, medium, or low in our case.

In order to ensure that both sides of an undivided highway are treated, each side of the road must have its own “stop” and vehicles must be constrained from crossing from one side of the road to the other within a given road segment. This constraint is critical because it is unrealistic for an RSIC vehicle to make a U-turn in most areas of typical undivided highways except at designated locations.

Once the network has been configured with the appropriate stops, the vehicle-routing problem generates the most efficient routes to service the stops in its service territory. An extension of the vehicle-routing problem, called the capacitated vehicle-routing problem, adds the vehicle-specific capacity constraint, to ensure that the total demand along a specific vehicle route does not exceed the capacity of that vehicle. The function outputs complete vehicle routes, including any necessary deadheading to get from the garage to the start of the service. Therefore, TransCAD’s capacitated vehicle-routing problem functionality was selected as the procedure to be used to determine complete statewide RSIC route systems for each scenario modeled.

While the capacitated vehicle-routing function has many features that align well with the research objectives of this project, by default, the function minimizes fuel consumption, rather than system service time. The function does allow the user to specify a time window for each stop within which that stop must be serviced, however, and by including these constraints, it is possible to create scenarios where the output produced by minimizing total VHTs largely converges with the minimum elapsed service time. The time window is effectively a maximum time limit for the elapsed service time at a specific garage. This convergence is produced by iteratively shrinking the time window for all of the stops associated with a given garage until either all available RSIC vehicles are deployed or the until further reductions in the time window would make it impossible to service all of the stops associated with that garage.

The efficiency of a set of vehicle routes could be measured either in terms of cumulative vehicle operating time (a proxy for fuel consumption) or in terms of the elapsed time until a specified set of road segments are serviced (hereafter service or completion time). Both of these efficiency metrics have desirable characteristics but they produce differing routing patterns as is shown in Figure 5 for a simplified network.

In Figure 5A, vehicle routing is optimized by minimizing fuel consumption. This goal is achieved by eliminating deadheading whenever possible, even at the expense of delaying service for some road segments. In the case of this simplified network, all road segments are assigned to a single vehicle even when a second vehicle is available and could be routed to reduce the time until all road segments are serviced. In Figure 5B, vehicle routing is optimized by minimizing elapsed service-time. Since both vehicles traverse the bottom segment of the network, cumulative fuel consumption increases relative to Figure 5A, but the elapsed time until the entire network is serviced is reduced.

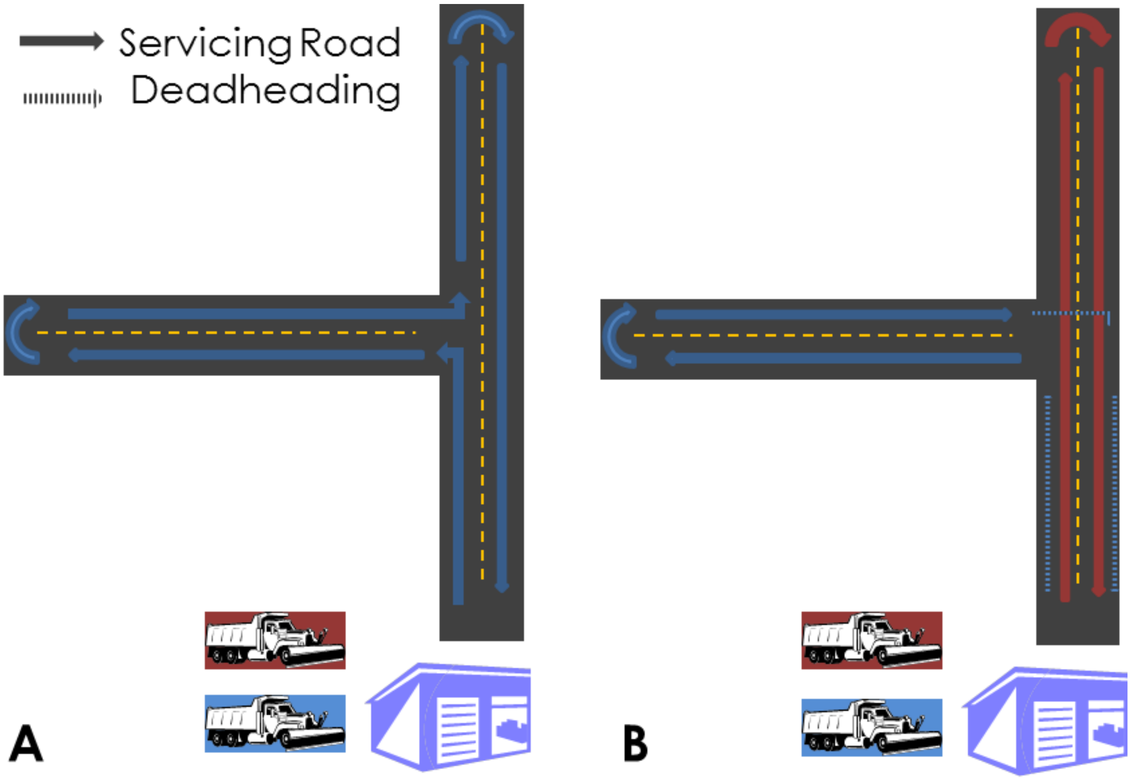

Figure 5 Alternative route efficiency metrics. A) Routing optimized by minimizing cumulative operating time (VHTs); no deadheading occurs B) Routing optimized by minimizing the elapsed time until all road segments are serviced; some deadheading occurs

For this project, route optimization was defined by a combination of elapsed service time and fuel consumption constraints. First, elapsed service-time constraints were imposed on each road segment that could only be satisfied by routing all of the vehicles assigned to each garage. Within these time constraints, vehicle routes were created to minimize fuel consumption. Vehicle routes were created using TransCAD's capacitated vehicle-routing function with user-specified time windows. The time windows establish maximum elapsed service times for each garage. This function was run sequentially for each of the 61 garages and their associated service territories. Travel times for the RSIC vehicles were assumed to be reduced when the routes were created. These reduced travel times were based on the suggested maximum travel speeds during storm events shown in the Snow and Ice Control Plan (VTrans, 2012) – see Figure 6.

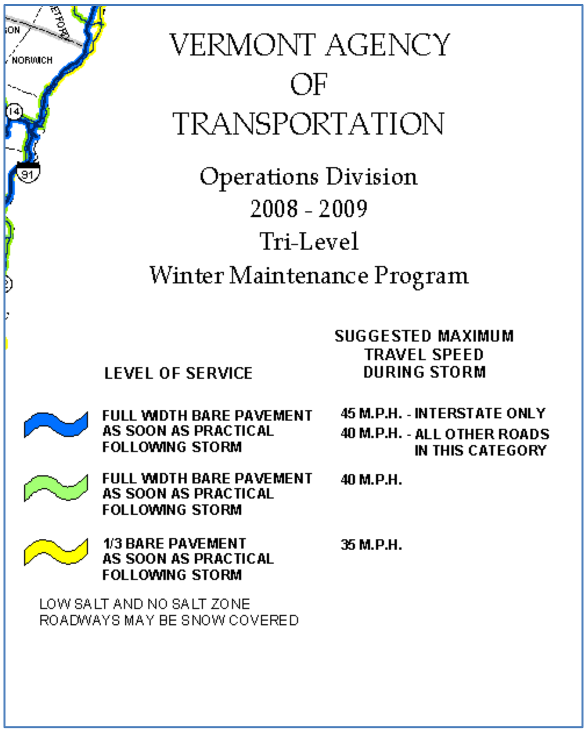

Figure 6 Suggested Maximum Travel Speeds During Winter Storms

The outputs of the function were a route-system that services all of the road segments within that territory, a total elapsed service-time, and a total VHT. As discussed previously, the capacitated vehicle routing function optimizes routes by minimizing fuel consumption rather than service time. Thus, in the absence of a binding time constraint on when individual stops must be serviced, the function will route the minimum number of vehicles required to service all road segments, often resulting in unused vehicles and unnecessarily long service times for some road segments. By specifying progressively shorter time windows in which all stops must be serviced, the function can be forced to route all of the vehicles (up to the vehicle saturation point) at each garage. These results provide routes that minimize fuel consumption given service time requirements, balancing the two competing efficiency metrics. Since the time window that produces these optimal results differs for each garage, vehicle allocation and storm type, calculating the optimal time window is an iterative process. Once a set of routes were created, the time window for garages that had unused vehicles was reduced, and the routing was repeated.

First, maximum and minimum elapsed service-times were established for each garage. The minimum elapsed service time was the time required to complete the longest round-trip in the service territory of a given garage. The maximum elapsed service-time was initially unlimited, but once an initial set of routes had been developed, it was set to equal the elapsed service-time for the longest route, plus 30 minutes. Following each iteration of the vehicle-routing procedure, the following adjustments were made to the time windows to minimize total elapsed service time and total VHTs:

- The time windows for garages with unused vehicles were reduced by 75% of the difference between the current elapsed service-time and the minimum time window

- The time windows for garages with “orphans”, or unserved stops in their service territory, were increased by 50% of the difference between the maximum time window and the current elapsed service-time.

Iterations of these adjustments to time windows were repeated until the minimum and maximum time windows at each garage converged. The TransCAD procedure requires that each garage have a single time window for all of its routes. Some additional gains in elapsed service-time would likely result from the use of route-specific time windows, especially at garages with relatively large service territories.

Once the time windows had converged, garages that were still over-saturated were identified and trucks were re-allocated as described in Section 2.2.3. After re-allocations were completed, the vehicle-routing procedure was again iterated until the time windows converged, and the search for over-saturated garages continued. This process, illustrated in a flow diagram in Figure 7, was repeated until no over-saturated garages remained.

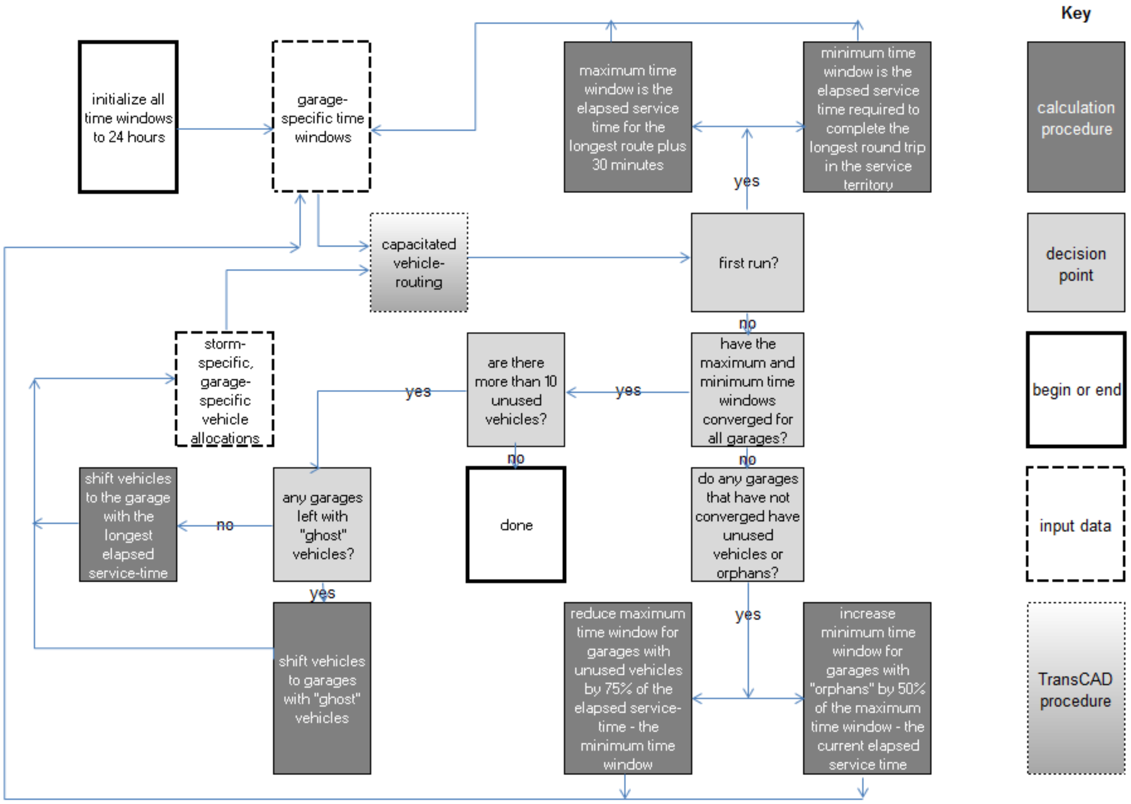

Figure 7 Flow Diagram for the Vehicle-Routing / Allocation Iterations Process

This routing/allocation process was conducted for three storm-intensity scenarios corresponding to a high-intensity event requiring a salt-application rate of 800 lbs./mile, a medium-intensity event requiring a salt-application rate of 500 lbs./mile, and a low-intensity event requiring a salt-application rate of 200 lbs./mile.

Finally, routing for the high-salt event was conducted using an unlimited RSIC vehicle fleet. This additional scenario served two purposes. First, it provides information about the number of vehicles that must be allocated to saturate each garage's service territory. Second, since winter storm events often impact some portions of the state more heavily than others, vehicles may be shifted from one garage to another based on local conditions. The results of the unlimited vehicle allocation therefore provide guidance on how unused vehicles in one part of the state can be routed most advantageously if deployed to another part of the state.

2.4 Evaluation and Comparison of Vehicle Allocations

As explained previously, the vehicle allocation is critical in providing efficient coverage of RSIC on all of the roads the state if responsible for. One of the most useful outcomes of this project is to identify garages where the existing allocation differs significantly from the allocations recommended in each of the approaches for each of the storm intensities. In addition, it is useful to compare each approach with the existing statewide allocation.

The individual garage-level allocations were compared using the absolute percent error (PE):

$$PE_i = \frac{\left|N_i - N_i^{obs}\right|}{N_i^{obs}} \tag{5}$$

where N_i^{obs} is the observed number of trucks allocated to garage i.

The statewide allocations (n = 61 garages) were compared using the mean absolute normalized error (Hollender and Liu, 2008):

$$\mathrm{MANE} = \frac{1}{n} \times \sum_{i=1}^{n} \frac{\left|N_i - N_i^{obs}\right|}{N_i^{obs}} \tag{6}$$

2.5 Evaluation and Comparison of Vehicle Routes

Once the vehicle routing problem had been solved for each garage, and 10 sets of vehicle routes had been optimized, the route systems were compared using a variety of performance metrics. It was not feasible for the designed routes to be compared to the existing routes, since the existing routes are currently not in electronic format. The performance metrics used to compare the optimized routes includes the total VHTs for all RSIC vehicles to cover the entire system of roadways the state is responsible for, the duration of the longest single route, the average route length, the time required to service all of the roadways in the network, and the time required to service 90% of the most critical links in the network.

The total VHTs are an indication of the fuel and man-hours that will be needed to implement each route system, so it is a good proxy for the costs that the Agency will incur. Tracking the longest single route and the time required to service all roadways in the network provides an indication of the speed with which the route system can be implemented. A comparison of these metrics reveals whether the existing fleet of 249 trucks is adequate to service all roadways (the two metrics are equal) or a subset of the trucks need to cover a second route before the entire route system is completed (the time required to service all roadways is greater than the longest single route). The time required to service 90% of the most critical links in the network provides an indication of the effectiveness of each route system in returning the capacity of the state's roadways to best serve the greatest number of Vermonters in serving their travel needs.

A comparison of the longest routes, the average route length, and the service times between the different allocation approaches also provides an indication of the level of equity afforded to each district. Route systems with a higher ratio of longest route length to average route length provide a less equitable distribution of resources amongst garages, since lower truck allocations are undoubtedly contributing to longer routes at some garages so that more trucks can be allocated to higher-priority garages, allowing the higher-priority service territories to be serviced faster.

3 Data Sources and Data Preparation

The road network from the Vermont Travel Model (Sullivan and Conger, 2012) served as the starting point for this project. This road network includes all of the roads in the state that the Agency is responsible for, along with certain other minor roads and urban roads that provide the network with continuity for routing simulations. Therefore, not all of the roadways in the Model road network are the responsibility of VTrans. The Agency's responsibility generally encompasses the interstate highways, federal highways, and state highways. However, the roadways in the Model that are not the responsibility of the state are still needed to provide the most efficient routing options for travelers and for RSIC vehicles. The Model is maintained and hosted by the UVM TRC through a cooperative agreement with the VTrans Division of Policy, Planning, and Intermodal Development.

The Model network, though, required a number of modifications in order to be compatible with TransCAD's capacitated vehicle-routing function. First, dummy turnarounds were added to the network at the state border for each divided highway. Without these turnaround points, divided highway segments beyond the final Vermont exit would be inaccessible to RSIC vehicles.

Figure 8 Dualized Links for RSIC Routing in Morrisville

Next, undivided roadways within the Model were converted into matched pairs of unidirectional roadways using TransCAD's "Dualize Segment" tool. This process ensured that during the optimization process RSIC vehicles traverse each road segment in its entirety. This procedure was only run for roadways that are the responsibility of the state, since it would only affect serviceable links that required snow and ice control. An example of the resulting dualized links is illustrated in Figure 8.

Once the network had been converted to unidirectional highway segments, the NRI and VTrans' road priority and speed data were specified for each road segment using TransCAD's "tagging" function, which allows coincident data to be transferred from one layer to another.

The Agency's "Snow and Ice Control Plan for State and Interstate Highways" for 2012 provides highway priority-ratings for RSIC activities as well as suggested travel speeds for RSIC vehicles (VTrans, 2012). A roadway GIS layer was obtained through the Vermont Center for Geographic Information (VCGI), which contained the priority ratings for each state-responsible roadway. VTrans' personnel provided a GIS data layer that included highway corridor priority ratings.

Next, the 61 VTrans maintenance garages, which serve as the beginning and ending points for all of the RSIC routes, were added to the road network. Address data for these garages are accessible on the VTrans website. The addresses were downloaded, matched to building point in the E911 buildings layer for 2010, then matched to nodes in the roadway network.

Once the garages had been linked to the road network, a network-based matrix of travel-times was created in TransCAD using the Shortest Paths function to calculate the shortest travel-time between all of the garages and every "stop" on the road network. Travel speeds represent reduced maximum safe speeds from the VTrans Snow and Ice Control Plan (VTrans, 2012).

Finally, the RSIC vehicle fleet information was obtained, so that a truck table could be created for the vehicle routing problem in TransCAD. An initial truck table identifying each truck with a unique ID in MS Excel was obtained from the Central Garage Superintendent. This table contained an exhaustive description of each truck, including its salt capacity, but it was determined to have some errors in the locations of trucks. So the true allocations of the trucks had to be obtained from the WMPD (VTrans, 2013). However, it was assumed that the distribution of capacity at each garage was the same as shown in the Excel table received from Central Garage, since the trucks shown in the WMPD were either not identified by ID, or did not match any of the IDs from the Excel table.

In order to calculate NRIs for each of the three scenarios based on link criticality, the 2009 travel-demand matrix from the Vermont Travel Model was used (Sullivan and Conger, 2012). The demand matrix from the Model was derived from the spatial distribution of population and employment in the state, along with travel behaviors revealed by Vermont respondents to the 2009 National Household Travel Survey (Sullivan, 2011).

4 Results

4.1 Service Territory Assignment

Table 3 provides the basic summary statistics for the service territories assigned to each garage.

Table 3 Summary Statistics for Service Territories by Garage

	Longest Round-Trip Travel Time		Total Road Length		Priority 1 Total Road Length		NRI	
Garage Town (Name, if different)	Time (min.)	Rank	Length (mi.)	Rank	Length (mi.)	Rank	NRI (hrs per day)	Rank
North Hero	72	15	39	33	6	41	360	6
Highgate	46	55	73	29	33	11	30	31
St. Albans	56	42	69	22	22	36	144	10
Georgia	53	49	31	42	17	39	311	7
New Haven	71	19	29	3	18	20	795	3
Cambridge	60	36	44	28	0	44	105	14
Morristown (Morrisville)	77	11	75	4	4	42	176	9
Eden	64	29	28	51	0	44	15	39
Montgomery	81	5	58	57	0	44	99	16
Westfield	70	22	44	17	0	44	1	53
Irasburg	60	36	47	25	0	44	4	46
Derby (Derby Lower)	56	42	57	26	33	12	88	18
Westmore	46	55	23	55	0	44	0	55
Enosburg	80	7	35	5	0	44	52	26
Barton	72	15	46	15	36	18	9	43
Brighton (Island Pond)	62	31	53	32	0	44	0	57
Canaan	53	49	25	56	0	44	0	59
Bloomfield	56	42	35	43	0	44	0	61
Lunenburg	78	9	23	40	21	15	2	50
Lyndon (Lyndonville)	68	24	58	10	27	28	81	20
St. Johnsbury	89	3	115	9	81	2	27	32
Danville (West Danville)	82	4	35	21	19	21	16	37
Newbury	68	24	63	27	26	23	4	47
Orange	49	52	35	59	2	43	31	30
East Montpelier (North Montpelier)	58	40	38	36	14	26	88	19
Berlin (Central)	51	51	40	46	32	13	91	17
Williamstown	61	34	76	10	24	32	104	15
Middlesex	73	14	75	18	49	6	559	4

	Longest Round-Trip Travel Time		Total Road Length		Priority 1 Total Road Length		NRI	
Garage Town (Name, if different)	Time (min.)	Rank	Length (mi.)	Rank	Length (mi.)	Rank	NRI (hrs per day)	Rank
Waitsfield	60	36	35	38	0	44	106	13
Middlebury	58	40	123	13	12	34	132	11
Randolph	72	15	60	16	21	37	60	24
Royalton	74	13	76	6	47	7	41	27
Tunbridge	60	36	67	47	0	44	73	22
Bradford	81	5	28	30	26	27	12	41
Brandon	70	22	60	52	12	33	40	29
Rochester	63	30	24	34	0	44	0	58
Hartford (White River)	71	19	46	20	53	5	120	12
Woodstock	56	42	75	23	21	14	17	35
Mendon	49	52	37	58	13	31	17	36
Rutland	61	34	22	35	27	16	194	8
Castleton	72	15	36	12	27	22	61	23
Windsor	62	31	79	48	24	24	59	25
Reading	44	60	36	54	0	44	1	52
Clarendon	94	2	37	53	37	17	41	28
Dorset (East Dorset)	78	9	64	7	25	10	15	40
Londonderry	46	55	44	39	0	44	2	51
Chester	46	55	30	49	13	30	6	44
Weathersfield (Ascutney)	56	42	39	50	21	38	22	34
Springfield	55	47	38	41	26	19	16	38
Rockingham	71	19	41	45	42	9	23	33
Jamaica (East Jamaica)	62	31	28	44	0	44	4	45
Dummerston	65	28	101	8	59	4	372	5
Marlboro	75	12	16	60	13	29	0	60
Wilmington	68	24	42	31	11	35	3	48
Bennington	80	7	84	2	54	3	73	21
Colchester (Chimney Corners)	48	54	36	19	27	8	1,866	2
Ludlow	55	47	37	24	14	25	10	42
Sudbury	67	27	41	14	0	44	2	49
Thetford	46	55	52	37	12	40	0	54
Colchester	95	1	146	1	106	1	11,402	1
Readsboro	29	61	25	61	0	44	0	56

Figure 9 shows the reach of the service territory (in red) allotted to the Waitsfield garage. As evident in the figure, the Waitsfield garage service territory includes 35 miles of roadway, with the longest round-trip from the garage of approximately 60 minutes. The longest round-trip is likely to be from the garage to the north up

Route 100 and back. However, it should be noted that the service territory assigned to the Waitsfield garage does not include any Priority 1 roadways.

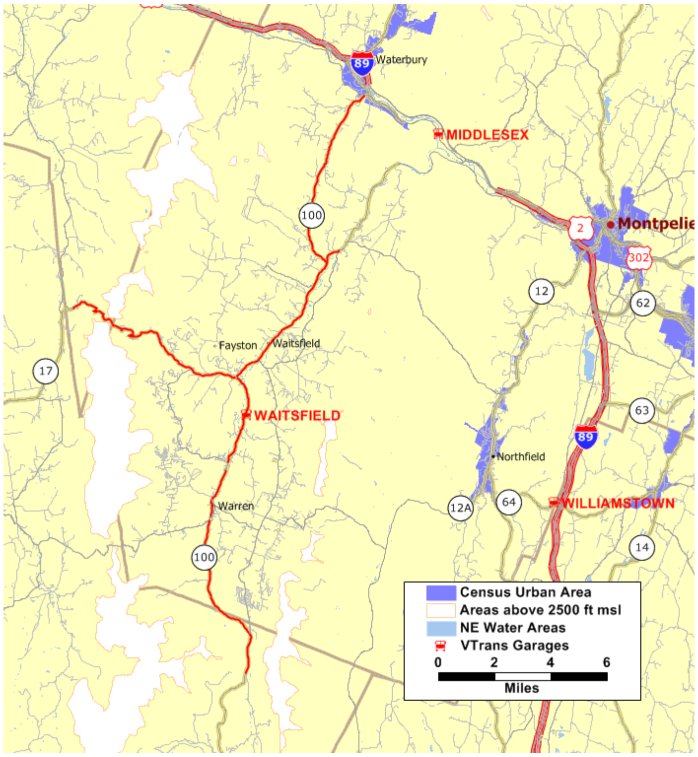

Figure 9 Service Territory of the Waitsfield Garage

Figure 10 shows the reach of the service territory allotted to the Morrisville garage (green roads). As evident in the figure, the Morrisville garage service territory includes 75 miles of roadway, with the longest round-trip from the garage of approximately 77 minutes. The longest round-trip could be from the garage to the north out to Route 14, or it could be to the south down Route 100 and Route 108. The Morrisville garage does include 4 miles of Priority 1 roadway, at the southernmost extent of Route 100 in its service territory.

Since the traditional district boundaries were ignored during the service territory assignment, many of these service territories cross into other districts.

Table 4 summarizes the averages, maxima and minima for each of the summary statistics across all service territories.

The variety of the lengths of the longest round-trips between garages is an indication of how inequitable the service territories are. The longest round-trip from a garage, 95 minutes, occurs in the Colchester garage service territory; whereas the average longest round-trip travel time is 64 minutes. The Colchester garage is also the location of the service territory with the longest total road length (146 miles), the highest level of road criticality (11,402 mile-hours per day), and the most Priority 1 roadways (106 miles).

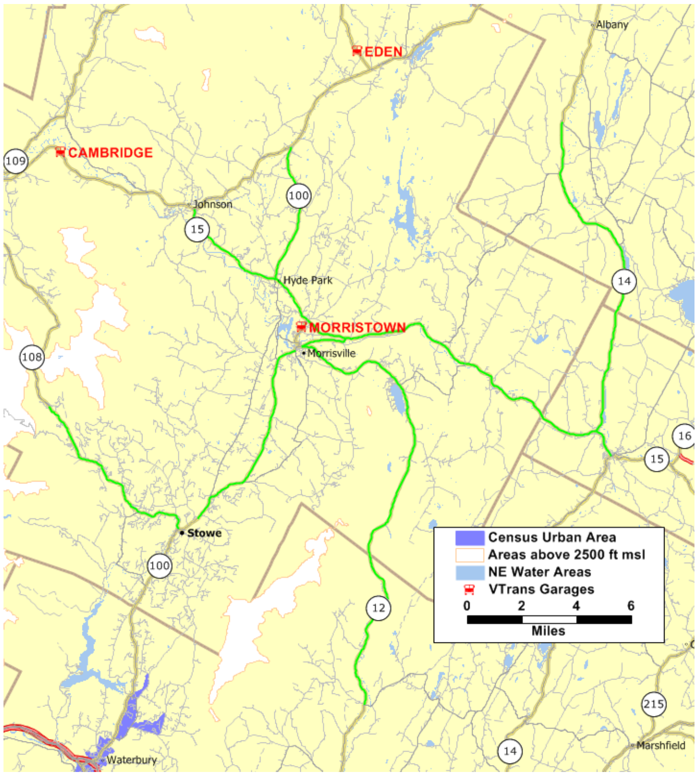

Figure 10 Service Territory of the Morrisville Garage

Table 4 Summary Statistics for All Service Territories

	Sum	Average	Maxima	Minima
Longest Round-Trip Travel Time (min.)		64	95	29
Road Length (mi.)	3,071	50	146	16
NRI (mile-hours per day)	17,983	295	11,402	0
Priority 1 Road Length (mi.)	1,205	20	106	0

4.2 Vehicle Allocations

Table 5 provides the vehicle allocations that resulted from each of the approaches used, at each of the three storm levels simulated. The percent errors calculated between the allocation and the existing allocation is also provided.

Table 5 Summary of Vehicle Allocations

Garage Town (with name, if different)	Current No. of Trucks	Low-Salt Truck Allocations						Medium-Salt Truck Allocations						High-Salt Truck Allocations							
		Road Length		Road Length ÷ Priority		Road NRI		Road Length		Road Length ÷ Priority		Road NRI		Road Length		Road Length ÷ Priority		Road NRI		Unlimited Trucks	
		No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE
Barton	3	5	40%	5	40%	5	40%	4	25%	5	40%	6	50%	4	25%	4	25%	5	40%	6	50%
Bennington	10	6	67%	6	67%	9	11%	6	67%	6	67%	9	11%	7	43%	8	25%	8	25%	6	67%
Berlin (Central)	0	3		4		4		3		4		4		3		4		3		7	
Bloomfield	1	3	67%	3	67%	2	50%	3	67%	3	67%	3	67%	3	67%	2	50%	2	50%	3	67%
Bradford	5	5	0%	5	0%	5	0%	5	0%	5	0%	5	0%	5	0%	5	0%	4	25%	6	17%
Brandon	2	3	33%	2	0%	3	33%	2	0%	2	0%	2	0%	2	0%	2	0%	3	33%	3	33%
Brighton (Island Pond)	5	3	67%	3	67%	3	67%	3	67%	3	67%	3	67%	4	25%	3	67%	4	25%	3	67%
Cambridge	4	4	0%	3	33%	5	20%	4	0%	3	33%	4	0%	4	0%	2	100%	4	0%	5	20%
Canaan	3	2	50%	2	50%	2	50%	2	50%	1	200%	1	200%	2	50%	1	200%	2	50%	2	50%
Castleton	7	6	17%	6	17%	4	75%	6	17%	6	17%	5	40%	6	17%	6	17%	5	40%	6	17%
Chester	3	2	50%	3	0%	3	0%	3	0%	3	0%	2	50%	2	50%	2	50%	2	50%	5	40%
Clarendon	4	4	0%	4	0%	4	0%	4	0%	4	0%	3	33%	5	20%	6	33%	5	20%	4	0%
Colchester	8	10	20%	10	20%	10	20%	11	27%	11	27%	11	27%	13	38%	16	50%	13	38%	10	20%
Colch. (Chimney Corners)	4	3	33%	4	0%	5	20%	3	33%	4	0%	5	20%	3	33%	4	0%	5	20%	5	20%
Danville (West Danville)	2	3	33%	3	33%	3	33%	4	50%	3	33%	3	33%	3	33%	3	33%	5	60%	4	50%
Derby (Derby Lower)	5	5	0%	6	17%	4	25%	5	0%	6	17%	4	25%	5	0%	6	17%	4	25%	6	17%
Dorset (East Dorset)	7	5	40%	5	40%	4	75%	5	40%	5	40%	5	40%	5	40%	5	40%	6	17%	6	17%
Dummerston	8	8	0%	10	20%	9	11%	8	0%	10	20%	6	33%	8	0%	10	20%	5	60%	10	20%
E. Montpelier (N. Montpelier)	4	3	33%	3	33%	2	100%	3	33%	3	33%	3	33%	3	33%	3	33%	3	33%	3	33%

Garage Town (with name, if different)	Current No. of Trucks	Low-Salt Truck Allocations						Medium-Salt Truck Allocations						High-Salt Truck Allocations							
		Road Length		Road Length ÷ Priority		Road NRI		Road Length		Road Length ÷ Priority		Road NRI		Road Length		Road Length ÷ Priority		Road NRI		Unlimited Trucks	
		No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE
Eden	3	3	0%	2	50%	2	50%	2	50%	2	50%	2	50%	2	50%	1	200%	2	50%	3	0%
Enosburg	6	4	50%	4	50%	4	50%	6	0%	7	14%	6	0%	5	20%	3	100%	7	14%	5	20%
Georgia	2	3	33%	3	33%	4	50%	3	33%	3	33%	4	50%	3	33%	3	33%	3	33%	7	71%
Hartford (White River)	11	6	83%	8	38%	7	57%	6	83%	8	38%	10	10%	6	83%	8	38%	5	120%	8	38%
Highgate	6	6	0%	6	0%	4	50%	6	0%	6	0%	4	50%	6	0%	6	0%	4	50%	9	33%
Irasburg	5	4	25%	4	25%	3	67%	4	25%	3	67%	4	25%	4	25%	2	150%	4	25%	5	0%
Jamaica (East Jamaica)	3	2	50%	2	50%	2	50%	2	50%	2	50%	3	0%	2	50%	2	50%	2	50%	3	0%
Londonderry	6	4	50%	3	100%	3	100%	4	50%	3	100%	3	100%	4	50%	3	100%	3	100%	5	20%
Ludlow	4	3	33%	3	33%	3	33%	3	33%	3	33%	3	33%	3	33%	3	33%	4	0%	5	20%
Lunenburg	3	3	0%	2	50%	2	50%	2	50%	2	50%	2	50%	2	50%	2	50%	3	0%	2	50%
Lyndon (Lyndonville)	7	5	40%	5	40%	5	40%	5	40%	5	40%	5	40%	5	40%	5	40%	5	40%	6	17%
Marlboro	2	1	100%	2	0%	2	0%	1	100%	2	0%	2	0%	1	100%	2	0%	1	100%	2	0%
Mendon	2	2	0%	2	0%	2	0%	2	0%	2	0%	2	0%	2	0%	2	0%	2	0%	2	0%
Middlebury	5	7	29%	7	29%	7	29%	7	29%	7	29%	7	29%	8	38%	9	44%	8	38%	7	29%
Middlesex	4	6	33%	7	43%	8	50%	6	33%	7	43%	7	43%	6	33%	8	50%	7	43%	7	43%
Montgomery	1	3	67%	3	67%	2	50%	3	67%	3	67%	2	50%	3	67%	3	67%	2	50%	3	67%
Morristown (Morrisville)	5	6	17%	5	0%	6	17%	6	17%	5	0%	5	0%	6	17%	4	25%	7	29%	7	29%
New Haven	5	6	17%	5	0%	7	29%	5	0%	5	0%	7	29%	5	0%	2	150%	7	29%	7	29%
Newbury	4	5	20%	5	20%	5	20%	5	20%	5	20%	4	0%	5	20%	5	20%	4	0%	6	33%
North Hero	3	3	0%	3	0%	3	0%	3	0%	3	0%	3	0%	3	0%	3	0%	3	0%	3	0%
Orange	2	3	33%	2	0%	2	0%	3	33%	2	0%	1	100%	3	33%	2	0%	2	0%	3	33%

Garage Town (with name, if different)	Current No. of Trucks	Low-Salt Truck Allocations						Medium-Salt Truck Allocations						High-Salt Truck Allocations							
		Road Length		Road Length ÷ Priority		Road NRI		Road Length		Road Length ÷ Priority		Road NRI		Road Length		Road Length ÷ Priority		Road NRI		Unlimited Trucks	
		No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE	No.	PE
Randolph	4	5	20%	4	0%	5	20%	5	20%	4	0%	5	20%	5	20%	4	0%	5	20%	6	33%
Reading	1	3	67%	2	50%	2	50%	3	67%	2	50%	2	50%	3	67%	2	50%	2	50%	4	75%
Readsboro	3	2	50%	1	200%	1	200%	2	50%	1	200%	1	200%	2	50%	1	200%	1	200%	2	50%
Rochester	3	4	25%	2	50%	3	0%	4	25%	3	0%	3	0%	4	25%	2	50%	3	0%	4	25%
Rockingham	3	4	25%	4	25%	4	25%	3	0%	4	25%	3	0%	3	0%	5	40%	2	50%	4	25%
Royalton	6	6	0%	7	14%	6	0%	6	0%	7	14%	6	0%	6	0%	7	14%	7	14%	10	40%
Rutland	5	3	67%	3	67%	5	0%	3	67%	3	67%	6	17%	3	67%	3	67%	3	67%	6	17%
Springfield	1	4	75%	4	75%	4	75%	3	67%	4	75%	4	75%	3	67%	4	75%	3	67%	6	83%
St. Albans	5	6	17%	5	0%	5	0%	6	17%	5	0%	5	0%	6	17%	5	0%	4	25%	8	38%
St. Johnsbury	6	7	14%	6	0%	6	0%	6	0%	6	0%	7	14%	7	14%	13	54%	6	0%	6	0%
Sudbury	3	4	25%	5	40%	4	25%	5	40%	4	25%	6	50%	3	0%	2	50%	5	40%	6	50%
Thetford	7	4	75%	4	75%	4	75%	4	75%	4	75%	3	133%	4	75%	4	75%	3	133%	8	13%
Tunbridge	1	2	50%	2	50%	2	50%	3	67%	3	67%	3	67%	2	50%	1	0%	3	67%	3	67%
Waitsfield	2	3	33%	3	33%	3	33%	3	33%	3	33%	3	33%	3	33%	2	0%	3	33%	4	50%
Weathersfield (Ascutney)	1	3	67%	4	75%	4	75%	3	67%	3	67%	3	67%	3	67%	3	67%	2	50%	5	80%
Westfield	7	4	75%	4	75%	3	133%	4	75%	3	133%	3	133%	4	75%	3	133%	5	40%	4	75%
Westmore	2	2	0%	2	0%	2	0%	2	0%	1	100%	2	0%	2	0%	1	100%	2	0%	3	33%
Williamstown	5	6	17%	6	17%	7	29%	6	17%	6	17%	5	0%	6	17%	6	17%	5	0%	8	38%
Wilmington	5	3	67%	4	25%	3	67%	3	67%	4	25%	3	67%	3	67%	4	25%	4	25%	4	25%
Windsor	4	3	33%	4	0%	4	0%	4	0%	4	0%	3	33%	3	33%	4	0%	4	0%	6	33%
Woodstock	1	3	67%	3	67%	3	67%	3	67%	3	67%	3	67%	3	67%	3	67%	4	75%	5	80%

Notes:

No. – Number of trucks assigned to each garage.

PE – Percent error between this allocation and the “Current No. of Trucks” column.

Table 6 provides a summary of the vehicle allocations for all garages, including the RMSPE for each approach at each storm intensity level. For all of the approaches, the maximum allocation of trucks occurred for the Colchester garage. For the unlimited approach, a total of 317 trucks were allocated to saturate all 61 garages and several garages were provided with 10 trucks (including Colchester).

Table 6 Summary of Vehicle Allocations for All Garages

Allocation Approach / Storm-Intensity	Max.	Min.
Low-Salt Scenario (200 lbs per mile)		
Roadway Length	10	1
Roadway Length ÷ Priority	10	1
Roadway NRI	10	1
Medium-Salt Scenario (500 lbs per mile)		
Roadway Length	11	1
Roadway Length ÷ Priority	11	1
Roadway NRI	11	1
High-Salt Scenario (800 lbs per mile)		
Roadway Length	13	1
Roadway Length ÷ Priority	16	1
Roadway NRI	13	1
Unlimited (317 Trucks)	10	2

4.3 Comparison and Evaluation of Vehicle Allocation Results

Overall, the vehicle allocation approaches and storm intensities perform similarly well in terms of their relationship with the existing allocation as measured by the MANE. Table 7 provides a summary of the MANE for each.

Table 7 MANE of Vehicle Allocation Approaches

Allocation Approach / Storm-Intensity	MANE
Low-Salt Scenario (200 lbs per mile)	
Roadway Length	47%
Roadway Length ÷ Priority	45%
Roadway NRI	46%
Medium-Salt Scenario (500 lbs per mile)	
Roadway Length	45%
Roadway Length ÷ Priority	46%
Roadway NRI	47%
High-Salt Scenario (800 lbs per mile)	
Roadway Length	44%
Roadway Length ÷ Priority	49%
Roadway NRI	46%

As measured by the MANE, the best fit to the existing allocation, on average, came from the Road Length approach, which did not include any “weighting” of roadways according to their priority level of modeled level of criticality. This result is not surprising, since the most intuitive allocation would likely be one based on total roadway miles. Any consideration of priority of criticality would require a level of modeling that is not known to have been done previously for RSIC planning. The MANE for the unlimited approach is not shown, since it is based on the allocation of a different number of trucks and routes than the existing allocation. The two other approaches performed equally well.

Of the three storm-intensities, the low- and medium-salt storm allocations performed equally well, and better than the high-salt storm. This result is also not surprising, since VTrans personnel reported that the high-salt storm intensity was a maximum level of salt that could be required, but was not a realistic estimate for a high-salt storm.

4.4 Vehicle Routing

Following the vehicle allocations, optimized RSIC routes were generated for each garage – one route was generated for each truck that had been allocated. Figure 11 shows the optimized RSIC routes generated for the Waitsfield garage for the low-salt storm, using the vehicle allocation based on link criticality, as measured by the NRI. As shown in the figure, deadheading is minimized by starting the three RSIC services provided by the three allocated trucks as close to the garage as possible. For this scenario, all of the routes are direct “out-and-back” types of routes, with no “looping”. Looping occurs when the routing problem solution provides for RSIC for each direction of a single link by a different route. These types of routes result when they are the absolute optimum.

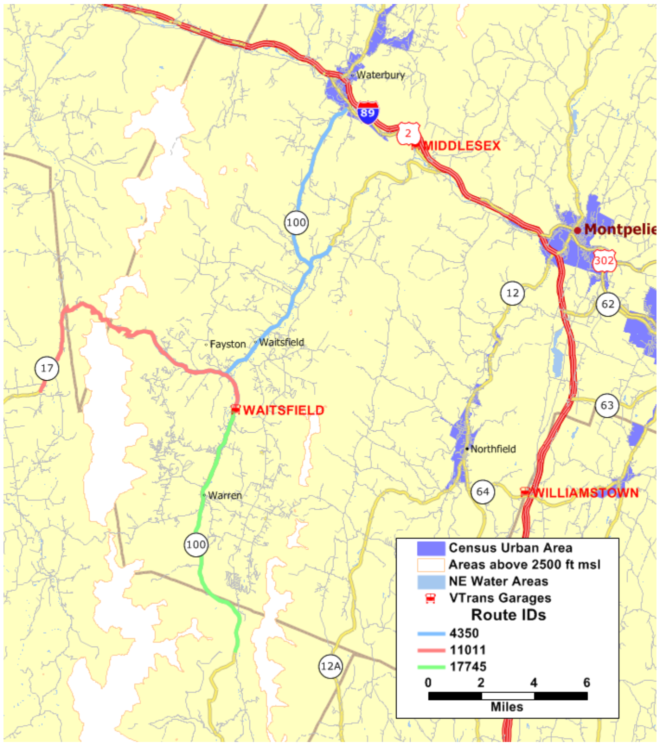

Figure 11 RSIC Routes for the Waitsfield Garage, Low-Salt Storm, Based on NRI

Figure 12 shows the optimized RSIC routes for the Morrisville garage for the same storm and the same allocation approach. Six routes were created for Morrisville to direct the RSIC of the six allocated vehicles at this garage. Four of the six routes are “out-and-back” routes, but the two routes indicated with the orange and red lines are looping routes. The red route proceeds counterclockwise from the garage to the east along Route 15, covers a short “out-and-back” portion of the Route 15 to the edge of its service territory, then proceeds north on Route 14 to the point where it meets the “out-and-back” route identified in yellow, returning south to deadhead along the town road traversed by the yellow route. This route leaves the opposing lane of traffic uncovered. The route identified in orange covers a few of the roads near the garage, then proceeds clockwise to oppose the red route, first deadheading east along Route 15, then deadheading along the town road to the north where the yellow route goes. The orange route turns south on Route 14 to oppose the red route, providing RSIC to the opposing lane of Route 14, then back west along Route 15, again providing RSIC to the lane opposing the red route.

A total of 2,490 route systems were generated, one for each RSIC vehicle, for each of the 10 scenarios listed in Table 6.

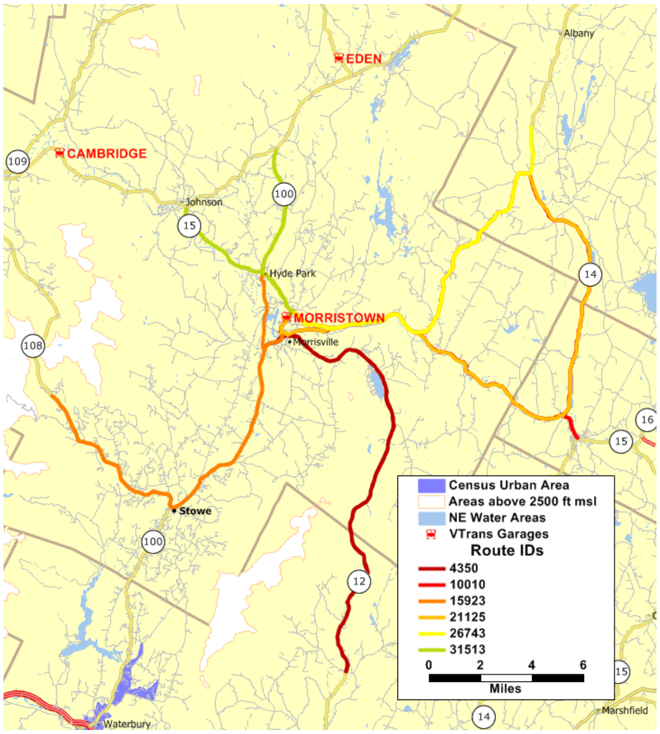

Figure 12 RSIC Routes for the Morrisville Garage, Low-Salt Storm, Based on NRI

4.5 Comparison and Evaluation of Vehicle Routing Results

Table 8 contains the performance metrics for each of the 10 RSIC route systems generated for this project.

An initial observation of the results is that the relationship between the salt requirements of the storm and the total VHTs required to provide RSIC services statewide are not linear. The requirements for the low- and medium-salt storms are both relatively easy to meet with the existing fleet without the need to return to a garage to re-supply. However, for the high-salt storm, existing vehicle capacities become relatively constrained, and a few second passes are required, as evidenced by the difference between the longest single route and the final service time for the “Roadway Length” and “Roadway Length ÷ Priority” approaches. For the high-salt scenario, the remarkable efficiency yielded by the approach simulating an “Unlimited” supply of vehicles is further evidence of the constraints placed on the existing vehicle fleet when large quantities of salt are required. As explained previously, though, it is acknowledged that this level of salt requirement is not common, particularly not throughout the entire state. Therefore, the best use of the route system created by the “Unlimited” scenario is to guide the need for “shifting” vehicles from one part of the state to another in the event of a predictably regional storm event.

Table 8 Performance for RSIC Route Systems

Allocation Approach / Storm-Intensity	90% NRI[1] (hrs)	Total VHTs	Longest Route[2] (hrs)	No. of Unused Vehicles[3]	Average Route Length (hrs)	Final Service Time[4] (hrs)
Low-Salt Scenario (200 lbs per mile)						
Roadway Length	1.37	281	2.1	4	1.15	2.1
Roadway Length ÷ Priority	1.36	282	1.7	0	1.13	1.7
Roadway NRI	1.36	280	1.9	6	1.15	1.9
Medium-Salt Scenario (500 lbs per mile)						
Roadway Length	1.29	282	2.5	9	1.18	2.5
Roadway Length ÷ Priority	1.24	286	1.8	5	1.17	1.8
Roadway NRI	1.26	280	2.0	8	1.16	2.0
High-Salt Scenario (800 lbs per mile)						
Roadway Length	2.04	298	2.3	6	1.23	4.3
Roadway Length ÷ Priority	1.52	306	2.5	7	1.26	4.0
Roadway NRI	0.99	304	2.7	0	1.22	2.8
Unlimited (317 Trucks)	1.28	299	1.6	0	1.20	1.6

Notes:

1. "90% NRI" refers to the total time it takes to provide RSIC service to roadways in the state whose cumulative NRI is 90% of the total.
2. The longest single route by any RSIC vehicle in the state
3. The number of RSIC vehicles remaining at all garages that never got routed, even after re-allocating unused vehicles once and re-running the vehicle routing procedure.
4. The total time to provide RSIC service to the entire statewide road network.

Some of the results are fairly intuitive, like the fact that the allocation approach based on the "Roadway NRI" generally captured 90% of the total NRI in the roadway-network the fastest. The only exception to this finding was for the medium-salt scenario, where it appeared as if the "Roadway Length ÷ Priority" approach performed even better. However, all of the results must be considered in the context of the number of unused vehicles left after the routing system was completed. It is likely that "Roadway NRI" approach for the medium-salt scenario was adversely affected by the 8 unused vehicles. Evidence for this finding can be found in the reduced number of VHTs taken by that approach (280, as opposed to 286 for the "Roadway Length ÷ Priority" approach), and the longer final service time (2.0 hours, as opposed to 1.8 hours for the "Roadway Length ÷ Priority" approach). These differences also provide evidence of the competing needs for each optimized route system to minimize VHTs and total service time. For most of the approach/scenario combinations, approach with the shortest final service time also incurred the largest number of VHTs. Therefore, more fuel is generally needed to complete the entire network faster.

However, this relationship does not hold for the time taken to provide service to 90% of the critical links in the network. For the allocations based on "Roadway NRI", the most optimal balance between service and fuel efficiency was reached. In every case, the "Roadway NRI" approach appeared to yield a route system with the best balance of fuel efficiency, speed to final service time, especially for the high-salt scenario, where capacity of the vehicles was most constrained. In fact, the "Roadway NRI" approach for the high-salt scenario was the only one (aside from the "Unlimited" approach) that did not require a second pass of any RSIC vehicle in the state, using every vehicle efficiently and effectively. With these considerations in mind, the Roadway NRI route systems appear to be the most effective, and are recommended for primary use in evaluating the existing allocations and route systems.

5 Discussion

The RSIC activities that VTrans undertakes in response to a given winter weather event depends upon a number of dynamic factors that cannot be fully accounted for in a finite number of modeling runs. These factors include storm duration, geographically variable storm-intensity and human factors such as traffic accidents, which can radically alter the RSIC services. Accordingly, any static set of vehicle route system will best serve as a starting point for an evaluation of RSIC operations and may have to be modified according the knowledge and expertise of the VTrans Operations staff.

In order to maximize the value of these research results, it is important, to discuss explicitly the modeling assumptions and data limitations that may cause divergences between model results and conditions on the ground for each of the research tasks. One known data limitation is that while there are turn-around points on the divided highways and on some undivided roadways that allow RSIC vehicles to reverse direction without looping or using access ramps, the locations of these turn-arounds are not precisely and exhaustively known. Therefore, they could not be included in the representation of the highway system. Consequently, the service-territory assignments will need to be updated.

After consulting with VTrans personnel, it has become clear that servicing both lanes of a divided highway may soon be possible with a “tow-behind” plow. Widespread use of the tow-behind units would require that the vehicle allocation be reconsidered and updated to reflect the additional trucks that would become available for reassignment and new routes.

Finally, the routes generated by this process are designed to service all road segments once. For many storms, the same road segment is likely to require multiple “passes” to reach performance goals for bare pavement. Since the routes presented here all return to their original garage, these routes can be repeated as many times as necessary of the course of a storm. However, the most optimal routing for repeated road coverage may not be identical to the routing required to cover all road segments once.

In spite of these limitations, this report provides several concrete items of information that can inform future RSIC operations in Vermont. The garage service-territory assignments provide the basis for a re-evaluation of the current district-based system. The unlimited vehicle-allocation provides information on the maximum saturation point for RSIC routing, which could be useful to consider shifting vehicles from one region of the state where a storm may not have reached, to another region which might be getting hit particularly hard by the same storm. Finally, the routes themselves provide a starting point for evaluating existing routes. Substantial deviations between the modeled routes and the current routes should be examined to see if they result from known limitations in the modeling process or from apparent inefficiencies in the existing routes.

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