Strategic Location of Satellite Salt Storage for Roadway Snow and Ice Control in Vermont

Final Report

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Executive Summary

Maintaining winter travel is one of the highest-profile activities of the Vermont Agency of Transportation (VTrans) and it can account for more than 10% of an entire annual VTrans budget. The state's snow and ice control operations are constrained by limited resources. Consequently, Vermont's Snow and Ice Control Plan sets out the objective of achieving "safe roads at safe speeds" as opposed to "bare roads", which may not always be feasible. The VTrans Plan establishes three levels of roadway service that are prioritized based on roadway classification, traffic volumes, and truck traffic. Winter maintenance objectives for all roadways in the state are based on those three roadway service classifications, and different roadways are given different priorities depending on their service classification.

Winter road maintenance planning in the state involves the application of different materials for roadway snow and ice control (RSIC). The application of the most appropriate material depends on the temperature, prevailing and expected weather conditions, and the desired level of service. Road maintenance materials include:

1) Salt, the primary material used;

2) Winter sand, generally used to provide traction at intersections and corners during icy conditions; and

3) Liquids, including salt-brine, chemical additives, liquid chloride blends, and anti-icing agents.

In 2013, this research team completed a study of optimized vehicle-routing for Vermont's RSIC fleet, incorporating a continuous measure of priority into an iterative heuristic solution. An important finding of that project was that snow plowing routes are highly constrained by salt loads during spreading operations rather than on fuel, resulting in plow trucks returning to their garage to refill salt well before they need to return for fuel. For that project, however, the storage locations of RSIC materials like salt were assumed to be fixed to the locations of VTrans garages. The purpose of this project was to build on those findings by exploring methods to strategically stage salt at satellite locations to make vehicle routing more efficient.

Our approach built on the concepts of traditional facility-location modeling in the operations-research literature. We also draw from the literature on emergency-response logistics modeling, which examines questions related to the location of emergency-support facilities and distribution centers, and the distribution and routing of emergency resources. There has been relatively little research specifically related to winter RSIC. A viable method was developed to site and rank locally-optimal SSFs for the distributed system of garages which serves to promote effective improvements to RSIC services by VTrans. The method identifies a locally-optimal location for each existing service territory, then evaluates and ranks their benefit to the network as a whole, in terms of the total lane-miles of state-maintained roadway brought to within 20 minutes of a salt loading location.

The results of an informal survey of satellite-salt siting practices amongst snow-belt DOTs are also reported. A critical aspect to siting new SSFs was found to be the ability to utilize existing right-of-way around interstates, and survey respondents

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note the need to explore public-private partnerships with landowners adjacent to the state highway right-of-way who may be willing to sell or lease small portions of cleared land for use as SSFs. Using the information from the survey, the research team compares a smaller set of "ready-to-use" SSF locations (with adequate right-of-way) to the locally-optimized SSF locations.

The Sharon rest area was found to be a viable ready-to-use SSF that can be used to offset RSIC costs. Other satellite salt facilities (SSFs) can best serve the state's RSIC operations by being sited near or on interstate highways, within the right-of-way of the existing infrastructure. The most effective locations are in Williston at the interchange of I-89 and State Route 2A, in Royalton at the underpass with Oxbow Road, and in Brattleboro at the interchange of I-91 and U.S. Highway 5.

1   Introduction

Maintaining winter travel is one of the highest-profile activities of the Vermont Agency of Transportation (VTrans) and it can account for more than 10% of an entire annual VTrans budget (VTrans, 2011a). The state's snow and ice control operations are constrained by limited resources. Consequently, Vermont's Snow and Ice Control Plan (VTrans, 2011b) sets out the objective of achieving "safe roads at safe speeds" as opposed to "bare roads", which may not always be feasible.

The VTrans Plan establishes three levels of roadway service that are prioritized based on roadway classification, traffic volumes, and truck traffic (VTrans, 2011b). Winter maintenance objectives for all roadways in the state are based on those three roadway service classifications, and different roadways are given different priorities depending on their service classification. Winter road maintenance planning in the state involves the application of different materials for roadway snow and ice control (RSIC). The application of the most appropriate material depends on the temperature, prevailing and expected weather conditions, and the desired level of service. Road maintenance materials include:

1)   Salt, the primary material used;

2)   Winter sand, generally used to provide traction at intersections and corners during icy conditions; and

3)   Liquids, including salt-brine, chemical additives, liquid chloride blends, and anti-icing agents.

In 2013, this research team completed a study of optimized vehicle-routing for Vermont's RSIC fleet, incorporating a continuous measure of priority into an iterative heuristic solution (Dowds et. al., 2013). An important finding of that project was that snow plowing routes are highly constrained by salt loads during spreading operations rather than on fuel, resulting in plow trucks returning to their garage to refill salt well before they need to return for fuel. For that project, however, the storage locations of RSIC materials were assumed to be fixed to the locations of VTrans garages. The purpose of this project is to build on the findings in that previous project by exploring methods to strategically stage salt and other RSIC control materials at satellite locations to make vehicle routing more efficient.

The objective of this project is to improve the effectiveness of winter RSIC activities by optimizing the storage locations of winter RSIC materials throughout the state. This paper considers the use of satellite salt facilities (SSFs), as a supplement to salt storage at existing garages, and introduces a method to strategically locate these SSFs to improve RSIC operations. A method for identifying locally-optimal SSFs is demonstrated, and SSF locations are ranked based on which locations are most effective at reducing the time plow trucks must travel to reload salt. The approach is consistent with the RSIC management practices currently followed in Vermont, and uses the real-world RSIC service territories in the state. Operational feasibility of potential SSF locations is also considered in two ways. First, site-specific aspects of existing SSFs are surveyed amongst other snow-belt DOTs. Next, these site-specific characteristics are used to suggest sites for the SSFs identified using the method of local-optimization.

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Our approach builds on the concepts of traditional facility-location modeling in the operations-research literature. Recent literature on facility-location modeling that relates to this research includes work done by Farahani et al. (2010) and Şahin and Süral (2007). These papers offer detailed discussions on approaches and techniques for facility-location modeling that can be directly applied to the problem of winter RSIC materials. We also draw from the literature on emergency-response logistics modeling, which examines questions related to the location of emergency-support facilities and distribution centers, and the distribution and routing of emergency resources. Emergency-response logistics can differ from more traditional facility-location problems in how vehicle availability, congestion, and temporal and spatial constraints are handled (Caunhye et al., 2012). There has been relatively little research specifically related to winter RSIC. However, Perrier et al. (2007) provide an excellent discussion of winter RSIC planning including the routing and location of plows, as well as spreading winter maintenance materials.

2 Data

This project used the TransCAD RSIC road network which had been developed and topologically corrected in the previous RSIC project (Dowds et. al., 2013), with some minimal modifications. Additional aerial photography from Google Maps was used to estimate the locations of closed interstate-highway rest areas (in Highgate, Randolph, Sharon, and Hartford) and other facilities which could serve as satellite salt depots.

The research team surveyed DOTs throughout the US about current approaches to strategically locate RSIC materials on the roadway network. This survey was conducted by email through the AASHTO Snow and Ice Listserv, maintained by researchers from the University of Iowa. The following questions were asked of participants on the listserv:

1) Does your agency strategically select snow and ice control routes to improve performance of snow and ice control activities?

2) If so, how frequently are these routes reviewed and updated?

3) Does your Agency strategically locate ice control materials (chemical and abrasive) at remote locations so trucks can restock without returning to their garage?

4) If so, how frequently are these locations reviewed and updated?

DOT RSIC managers from the seven states shown in green in Figure 1 responded to the survey.
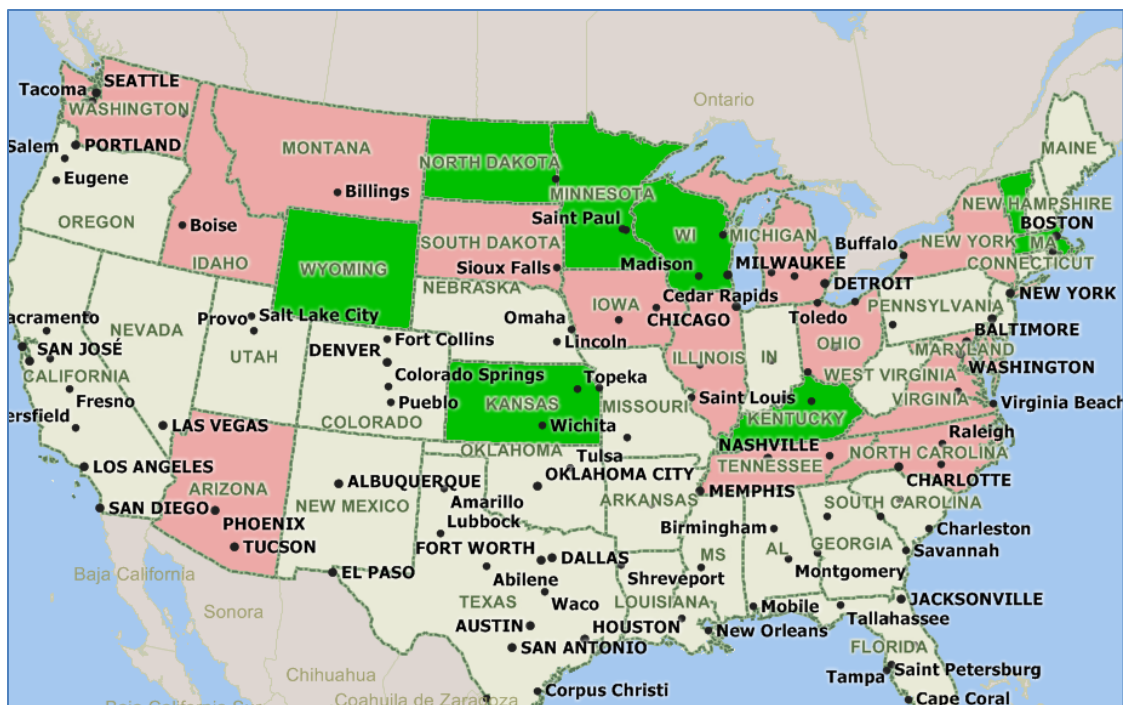
Figure 1 States Responding to the RSIC Survey Distributed Through the AASHTO Listserv (Green)

The states shown in pink responded to a previous survey about RSIC performance measures (Kipp and Sanborn, 2012), along with those shown in green. There may only be seven states which have considered the placement of salt as a factor in the effectiveness of their RSIC operations. The seven responses received for the survey conducted for this project are shown in Table 1.

Table 1 Responses to the RSIC Survey Distributed Through the AASHTO Listserv

	Question			
State	**1**	**2**	**3**	**4**
Paul Brown, Massachusetts	We are stuck by physical locations. History has showed us that we can't relocate many facilities.	We review spreader routes almost every year.	**We have satellite facilities that we can utilize when snow event warrant. We currently do not share a shed unless the municipality has requested short term assistance. We did it once last year when a municipal shed was not completed in time for winter.**	Again we are stuck by history.
Michael Sproul, Wisconsin	Not Yet. We are looking into using RouteSmart.		We are beginning to.	Only when building new sheds.

State	Question			
	1	2	3	4
David Cornett, Kentucky	Yes	Annually, when the Snow and Ice Control Plans are developed.	No	
Brandon Beise, North Dakota	No		**NDDOT places remote stockpile sites between maintenance sections or districts and at the ends of plow runs. North Dakota has 80 maintenance sections throughout the state and has 36 remote stockpile sites.**	These remote sites are reviewed annually in the Snow & Ice Control Plan and changed as operations evolve.
Cliff Spoonemore, Wyoming	No, we ran an equipment evaluation many years ago to determine the size of the truck fleet and manpower needs.	Not often enough	**We have some in place at the end of routes. We need to place more. At this time most are just sand/salt piles. They need to include chemicals to fill the saddle tanks.**	Yearly for inventory reasons. If they do have tanks they are inspected to prevent leaks.
Clay Adams, Kansas	We do not. We have submitted a research proposal to Clear Roads to see what tools are out there to help plan routes. We have 3 levels of priority, but the order they are treated is up to the Supervisor based on history.		**Yes. We have a number of concrete block bunkers with CoverAll roofs that hold 400-500 tons**	Each year we keep finding new locations to build one where more than one shop can use it. We try to build them half way between shops or at dead end locations.
Steven Lund, Minnesota	Routes have been developed over time and are reviewed yearly at the local level. Is that strategic - don't know?	Reviewed yearly, updated infrequently relative to the 602 plow routes.	Yes; however this is influenced by availability of ROW, partnership limitation, etc.	Reviewed yearly updated infrequently.

The responses shown in bold in the table indicate that satellite salt facilities are used in other states. To get more information on these practices, a follow-up question was asked of the four states which had responded affirmatively:

- Does your state DOT own the property at the locations where stockpiles are kept, or is an agreement with the property owner to use these locations temporarily?

Three of the four states responded to this question. These follow-up responses, with the initial responses to questions 3 and 4, are shown in Table 2.

Table 2 Initial Responses and Follow-Up Responses by North Dakota, Wyoming, and Kansas

State	Question		
	3	4	Follow-Up
Brandon Beise, North Dakota	**NDDOT places remote stockpile sites between maintenance sections or districts and at the ends of plow runs. North Dakota has 80 maintenance sections throughout the state and has 36 remote stockpile sites.**	These remote sites are reviewed annually in the Snow & Ice Control Plan and changed as operations evolve.	North Dakota DOT owns the land that the stockpiles are on. NDDOT has usually gained the property through uneconomic remnants from construction project right of way acquisitions. Several old rest areas have been closed and converted to stockpile sites.
Cliff Spoonemore, Wyoming	**We have some in place at the end of routes. We need to place more. At this time most are just sand/salt piles. They need to include chemicals to fill the saddle tanks.**	Yearly for inventory reasons. If they do have tanks they are inspected to prevent leaks.	WYDOT owns the land we place our storage sheds on. Along the Interstates we try to use the extra width at interchanges. One site is stored in the gore zone by the bridge abutment and start of the ramp. This is a small site. With our limited population and open space the landowners work with us a bit. We will not condemn for this property, so the landowner has to agree to our purchase. Our Right of Way Program does the purchasing and sometimes they offer fence line improvements (cattleguards, pipes) to offset the price a bit. If the landowner wants gravel for his road we have done that, but we cannot spread it for him. We have the truck dump and then he has to spread. R/W gets as creative as they can without breaking the bank.

	Question		
State	**3**	**4**	**Follow-Up**
Clay Adams, Kansas	**Yes. We have a number of concrete block bunkers with CoverAll roofs that hold 400-500 tons**	Each year we keep finding new locations to build one where more than one shop can use it. We try to build them half way between shops or at dead end locations.	We own the locations we have. They are typically areas where we bought extra R/W for mixing strips or storage of aggregates. We have one inside a loop at an intersection, but that is not our preferred location. We have partnered with some counties and have set up salt bunkers next to theirs. Now we are partnering with our turnpike authority and able to buy material from them. We have done this with some Cities at a few locations where they might have a salt storage facility on the outskirts of the city.

3   Methodology

Following the data collection, a review of research methods used to optimize facility-location and spreading of winter RSIC materials was conducted. In general, facility-location problems involve choosing the best location(s) from a set of possible candidate locations and/or determining the number of facilities needed to provide a particular level of service. Facility location models are used to find efficient locations for different types of facilities. For example, facility location models can be used to find optimal or potential locations for police stations, hospitals, warehouses, distribution centers, etc., based on different objectives such as improving the current level of service, reducing the overall cost of service, and/or maximizing profits. There are typically financial or operational constraints that affect the solutions. For example, there may be an upper limit on the number of facilities you are able to add, or a fixed budget for adding facilities. In other cases, revenues and profits may depend on the choice of locations and you would need to tradeoff between the costs associated with adding a new facility and the expected benefits. From this review, a facility-location method used to determine the optimal "warehouse" facility to add to a group of existing facilities was selected for this analysis.

3.1 Identification of SSF Locations

The research team employed two different approaches to identify SSF locations. The two approaches are referred to as: 1) locally-optimal, and 2) ready-to-use. In the locally-optimal approach, the facility-location tool built into the TransCAD™ software was used to identify the best SSF location for each of the 60 VTrans garage service areas. Individual SSF locations are locally optimized within the service area of each of the 60 existing VTrans garages. The locally-optimal SSF locations are "pinned" to the mid-point of a link in the state-maintained road network. Operational practicality of these sites was not explicitly considered during the

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optimization. For example, the facility location tool in TransCAD™ does not require that a serviceable turn-around be located near the suggested site or that roadway where the SSF site is located have shoulders wide enough to accommodate salt storage. Those considerations were made after the best locations had been identified and evaluated.

There are two possible limitations to this approach. The first is that the selected sites do not represent a globally optimal assignment for the entire RSIC fleet throughout the state of Vermont as a whole. However, optimizing the SSF locations locally for each service area is consistent with real-world operational constraints. In practice, state RSIC fleets are managed in individual service areas, as opposed to being managed as a single fleet. Managing all vehicles and garages as a single fleet is also less appealing when local weather fluctuations are considered. In Vermont, as in many snow-belt states, one part of the state may be experiencing severe winter weather while another part of the state is experiencing no precipitation at all. Concurrent dispatching of the entire statewide RSIC fleet is therefore uncommon.

The second possible limitation to this approach is that the location of the individual SSFs is, to some degree, based on the sequence in which the individual SSFs are assigned to each garage. Priority was assigned to the interstate-serving garages by separating these 22 garages from the 38 garages that service only non-interstate roadway segments. This prioritization approach is consistent with the RSIC management priorities of VTrans. However, the sequencing of individual SSFs within each priority group was random. Given the time and computing power needed to examine all different sequencing possibilities, and the fact that VTrans does not have a specific garage prioritization scheme, the team did not explore other sequencing approaches in detail, or evaluate each possible sequencing alternative.

The ready-to-use approach focuses only on SSF locations that are already operationally feasible. In the case of Vermont, ready-to-use SSF locations include four closed rest areas along the interstate-highways. The precise locations of these sites were identified and geo-referenced using Google Maps so a siting method was not needed.

3.2 Software Selection and Constraints

The TransCAD™ software platform was used to store, display, and manage data, as well as to conduct the facility-location analysis. TransCAD™ includes a set of general-purpose, built-in facility-location functions that facilitated the methodological approach used here. The team imposed a constraint of assigning, at most, one SSF to each of the 60 existing garages (and their corresponding service areas) from which RSIC vehicles are routed.

A series of custom scripts were created using TransCAD's™ built-in facility-location tool to identify locally-optimal SSFs by minimizing the total time to service all roadways within each garage's service area. The selection process was sequential and cumulative in nature, so the locations of any SSFs already created for other service areas were considered when siting new SSF locations. This cumulative

sequencing prevented the possible "edge effect" shown in Figure 2, in which a new SSF is located next to an existing SSF in an adjacent service area.
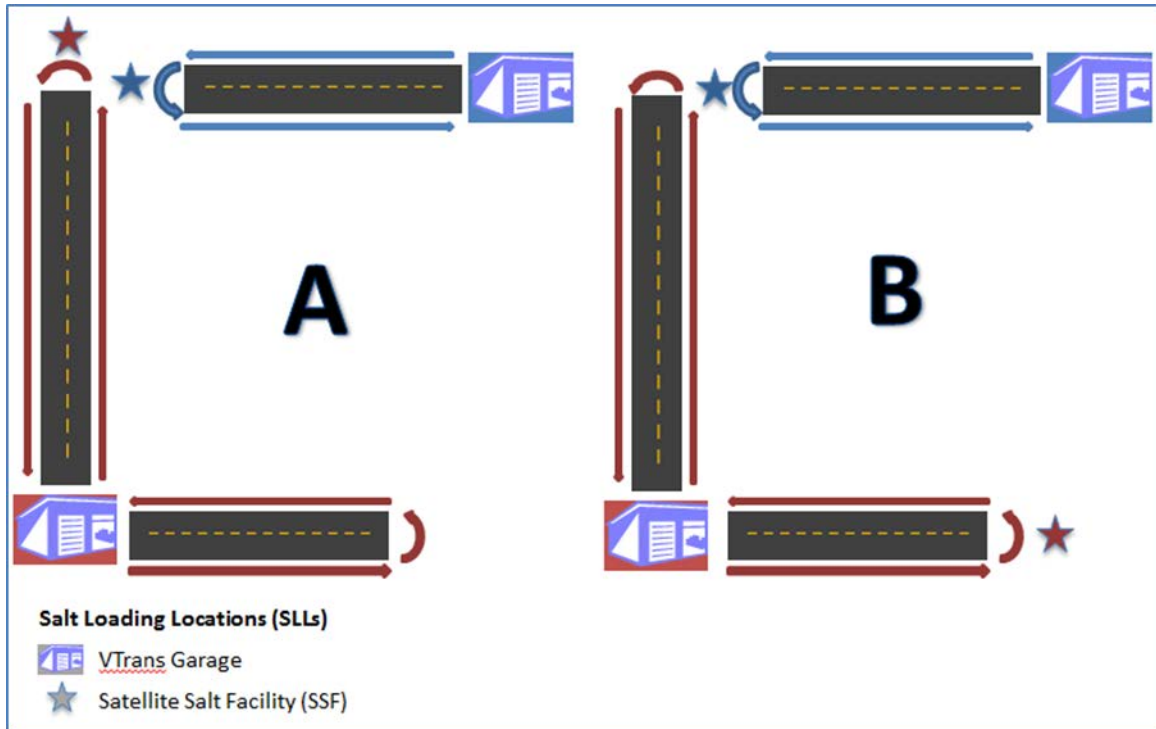
Figure 2 "Edge Effect" (A) SSF Identified Without Considering Existing SSFs and (B) SSF Identified Accounting for Existing SSFs.

Since the procedure used to locate each SSF location is sequential, it is therefore impacted by the order in which the garages are selected for the evaluation. As discussed in the December 11, 2013 Technical Advisory Committee (TAC) meeting for this project, the potential SSF locations for the garages that serve interstates were limited to interstate links. These SSFs are likely to decrease the time required to service non-interstate links as well, but that impact was not part of the optimization. In order to be consistent with operational practices which prioritize the interstates, the sequenced identification of SSFs was conducted first for the 22 interstate-serving garages, and subsequently for the 38 non-interstate serving garages. The sequencing of individual SSFs within each priority group was random.

An additional evaluation script was created using TransCAD's™ "Network Bands" tool to evaluate the effectiveness of each of the SSFs with respect to reducing RSIC-vehicle travel times. The "Network Bands" tool divides the road network into zones by travel time from a specific set of origins. The script was used to create five separate RSIC travel-time zones: 1) $x < 10$ minutes, 2) $10 \leq x < 20$ minutes, 3) $20 \leq x < 30$, 4) $30 \leq x < 40$ minutes, and 5) $x \geq 40$ minutes; where x is the minimum travel time from the nearest of the 60 existing VTrans garages to every point on the network. The script then calculates the total number of lane-miles that fall within each of the five zones in each garage's service area using TransCAD's™ "Column-Aggregate" tool.

The evaluation script was first run using all existing 60 garages to establish a baseline for the total lane-miles in each zone without any SSFs. The baseline served

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as a baseline (no SSFs) travel-time measure against which each of the SSF sites was compared. The script was then run 64 times; once for each of the 60 locally-optimized SSFs and then once for each of the four ready-to-use SSF locations.

3.3 Evaluation, Comparison, and Ranking of SSFs

The complete set of SSF locations and all existing VTrans garages function as salt loading locations (SLLs) – trucks can re-load salt at either their home garage or an SSF. Increasing the number of possible SLLs by adding SSFs can improve RSIC operations by enabling plow trucks to replenish on-board salt supplies without having to return to their home garage. This, in turn, reduces both deadheading and the time required to complete individual plow routes. The effectiveness of a SSF location can therefore be measured in terms of the reduction in the distance (in minutes) that a plow travels to get to the nearest SLL (either its garage or a SSF) from any point on the state-maintained roadway network.

To evaluate the impact of individual SSFs, the total lane-miles within each of the five travel-time zones ($x < 10$ minutes; $10 \leq x < 20$ minutes; $20 \leq x < 30$ minutes; $30 \leq x < 40$ minutes; and $x \geq 40$ minutes) for each SLL (including SSFs) were compared to the baseline scenario where only the VTrans garages served as SLLs (no SSFs). The plow speeds specified in the VTrans RSIC Plan (VTrans, 2011b) were used to determine travel-times in the network. Unlike the SSF site selection procedure, which was constrained by each garage's service area, the evaluation of the SSFs was conducted at the full-state level. The evaluation approach subsequently allowed multiple service areas to benefit from the same SSF, if the SSF is located near one or more service area boundaries. That is, individual SSFs strategically located to serve more than one service area will show an improved benefit.

The last step in the analysis was to rank order both the locally-optimal SSFs and the ready-to-use SSFs by comparing the allocation of lane-miles within each of the five zones for each SLL, for both the "garages + SSF" SLL scenario and the "garages-only" SLL scenario. The effectiveness of each SSF location was quantified based on the observed increase in the ability to "shift" the most lane-miles serviced to within the 20-minute coverage area of each SLL compared to the baseline scenario. For example, if the addition of an SSF resulted in "shifting" a relatively large number of lane-miles from more distant coverage zones (greater than 20 minutes from the SLL) to closer service-time zone (less than 20 minutes from the SLL), then the SSF was assumed to have a more positive effect on RSIC operations. The positive shift in service times is illustrated in Figure 3 for all SSF locations in the network as a whole.
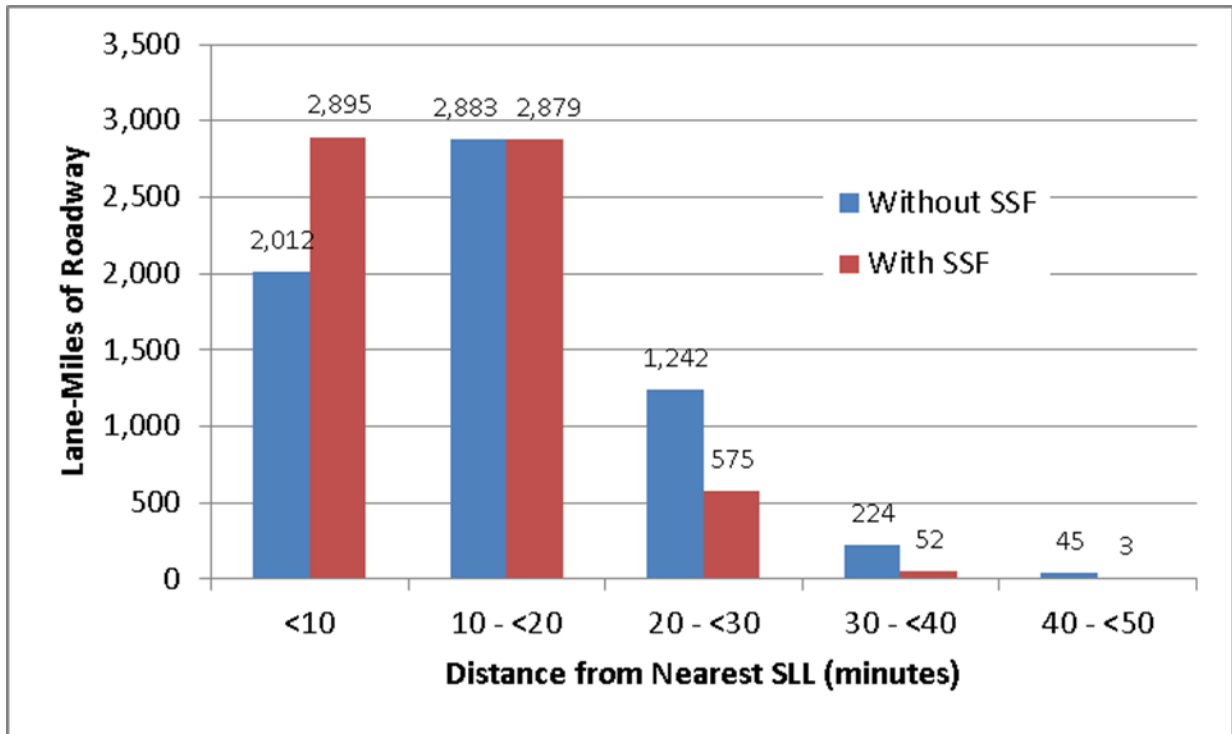
Figure 3 Shift in Distances to the Nearest Salt-Loading Location After the Addition of All Locally-Optimized Satellite Salt Facilities

The justification for choosing the 20-minute service-time threshold was based on the structure of the network system. Currently, the vast majority of the lane-miles in the existing state-maintained network that require servicing are 10 to 20-minutes from the nearest garage (see Figure 3). Therefore, establishing a generalized performance goal that is based on "shifting" as many lane-miles as possible from the more distant, outlying coverage zones (greater than 20 minutes) to under the 20-minute service time threshold was considered reasonable. In addition, the average farthest roadway from each garage is 33 minutes (Dowds et. al., 2013). This implies that setting a service-time threshold of 30-minutes would be too limited in scope to represent a value-added goal for the entire state. The 10-minute threshold was used as a secondary performance criterion to resolve "ties" in the ranking that resulted from the use of the 20-minute threshold.

Using the number of lane miles shifted under a service-time threshold as the performance criterion is consistent with the facility-location research literature. Modeling the location of important new facilities typically involves the use of performance criteria such as minimizing the average travel distance or travel time to the closest facility across a service network (Beraldi and Bruni, 2009; Taylor 2008). The effectiveness of emergency response services is often measured according to the coverage that is provided. For example, the percentage of all emergency calls that are responded to in less than 10 minutes might be a performance criterion.

All of the lane-miles in the dualized RSIC road network for the state of Vermont were used to evaluate the effectiveness of each SSF. The coverage area metric therefore represents an absolute measure of the effectiveness of each SSF and removes the effect of the varying sizes of the sub-networks within each garage's

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service area. This approach normalizes the results of the study to account for unequal sizes of service areas (in terms of both square miles and total lane miles) and provides a legitimate indication of where the state can get the most "bang for its buck" with respect to the selection of SSF locations.

The total number of lane-miles in the RSIC network (6,407) is smaller than the total number of lane-miles in Vermont's official federal-aid road network (8,531, as of 2011). As described in the previous RSIC project (Dowds et. al., 2013), the RSIC lane-miles only included road segments that the state is responsible for servicing and thus federal-aid roads within town centers, that VTrans does not plow, are not included in this number.

4 Results

The locations of all SSFs, both locally-optimal (identified using the TransCAD scripts) and ready-to-use (identified in Google Maps at closed rest areas), are shown in Figure 4.
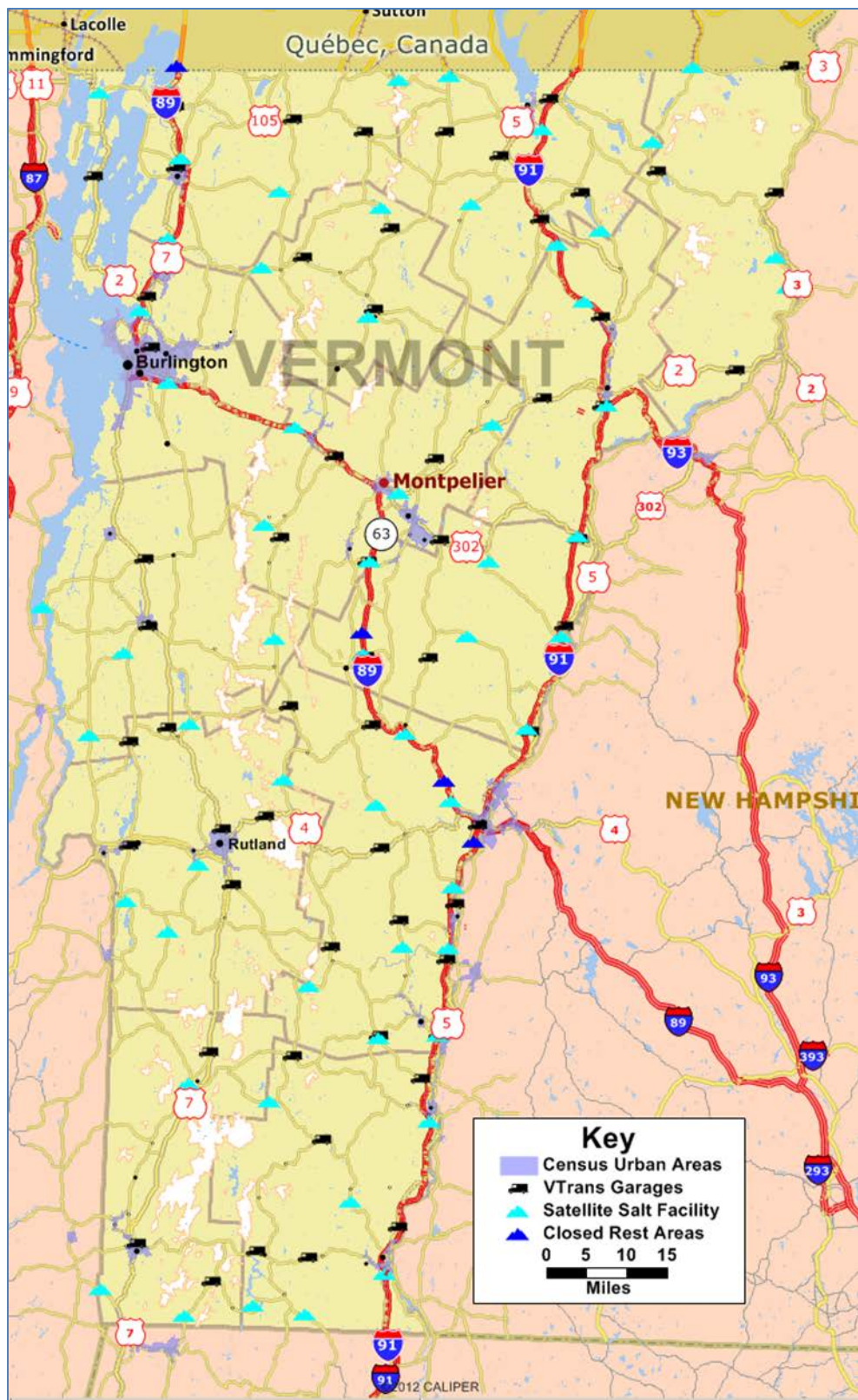
Figure 4 Locations of Potential Satellite Salt Facilities in Vermont

The results are discussed separately for the locally-optimal set of SSFs and the ready-to-use set of SSFs. In the case of the locally-optimal set of SSFs, the results are further classified based on their effects on interstate-highway lane-miles and non-interstate-highway lane-miles, consistent with VTrans operational priorities discussed earlier.

Since all four of the closed rest-areas included in the ready-to-use set of SSFs are on interstates, there was no need to further stratify those results.

4.1 Locally-Optimal SSFs

4.1.1 Interstate SSFs

In Figure 5, the evaluation results for the Williston and Hartland SSF locations are presented to illustrate the shifting in the interstate-highway lane-miles within each of the five zones compared to the base case.
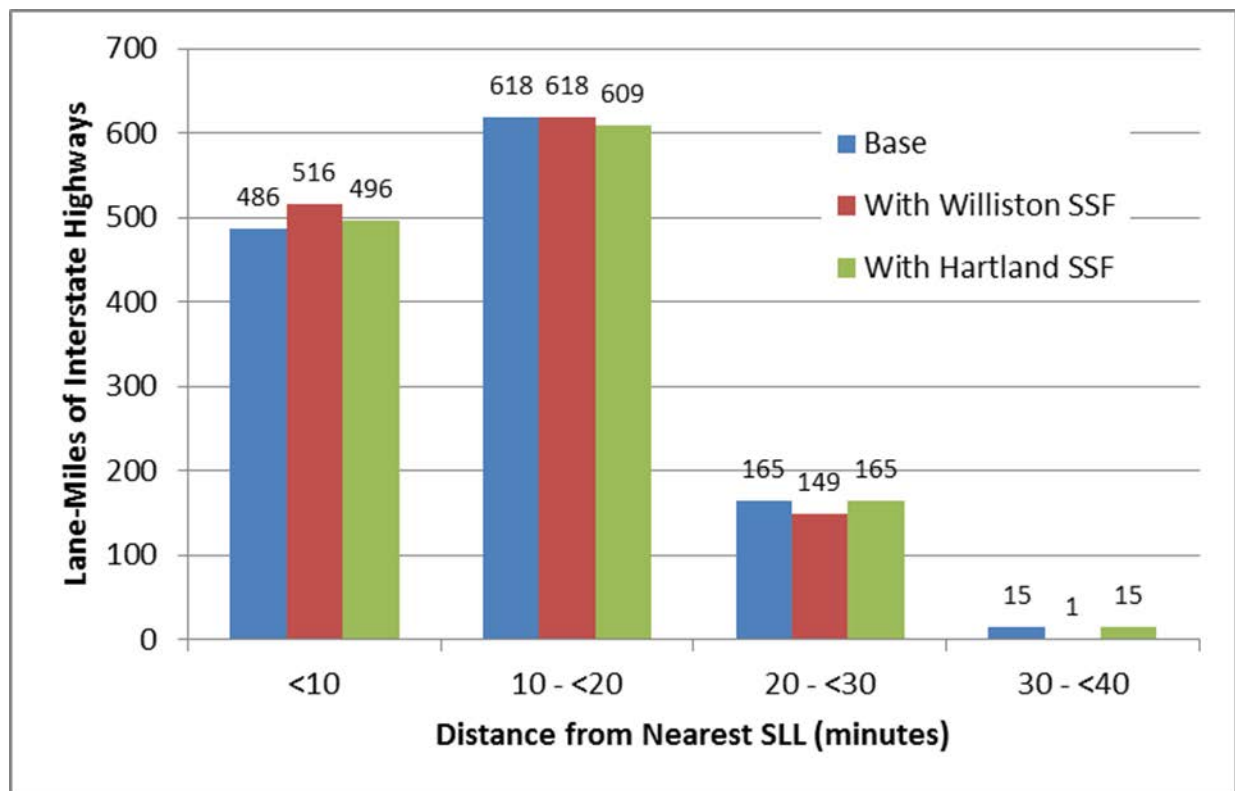

Figure 5 Changes in Interstate Lane-Miles for the Williston and Hartland Satellite Salt Facilities

For the interstate SSFs, there are no lane miles that are more than 40 minutes from a SLL, so the $x \geq 40$ minutes zone is not shown. When considering the impact each SSF has on the reduction in the total lane-miles greater than 20 minutes from a

SLL, the Williston SSF has a far greater impact (shifting 30 lane-miles) than the Hartland SSF (shifting 0 lane-miles). The Williston SSF provides a 16-mile reduction in the $20 \leq x < 30$ category and a 14-mile reduction in the $30 \leq x < 40$ category. Consequently, the Williston SSF is ranked more highly than the Hartland SSF.

Table 3 provides the rank order for all interstate SSFs (from most effective to least effective), along with the corresponding changes in the total lane-miles within each service time category.

Table 3 Rank Order of Interstate Satellite Salt Facilities

| Satellite Salt Facility Location | Change in the number of lane miles within the given time interval (in minutes to the nearest SLL) | | | | | | | | |
| | Interstate lane miles | | | | | Non-interstate lane miles | | | |
	<10	10-<20	20-<30	30-<40	20+	<10	10-<20	20-<30	30-<40
Williston	30	0	-15	-14	**-30**	27	23	-28	-22
Royalton	12	17	-29	0	**-29**	5	13	-17	0
Brattleboro	26	-4	-22	-1	**-23**	11	5	-12	-4
Westminster	20	0	-20	0	**-20**	8	3	-11	0
Hartford	13	4	-17	0	**-17**	4	4	-7	0
Newbury	3	3	-6	0	**-6**	1	2	-3	0
Waterbury	12	-7	8	-13	**-5**	7	-5	8	-9
Bradford	21	-16	-4	0	**-4**	7	6	-12	-1
Derby	14	-11	-3	0	**-3**	0	0	0	0
Waterford	8	-5	-3	0	**-3**	8	-1	-6	0
Sheffield	31	-30	-1	0	**-1**	7	-6	-1	0
Wheelock	10	-8	-1	0	**-1**	1	0	-1	0
Randolph	2	-1	-1	0	**-1**	0	0	0	0
St. Albans	25	-25	0	0	**0**	18	-18	0	0
Highgate	17	-17	0	0	**0**	6	-6	-1	0
Hartland	10	-10	0	0	**0**	8	-7	0	0
Williamstown	9	-9	0	0	**0**	6	-5	-1	0
Colchester	6	-8	0	0	**0**	0	0	0	0
Georgia	6	-6	0	0	**0**	3	4	-7	0
Thetford	3	-3	0	0	**0**	1	-1	0	0
Weathersfield	2	-2	0	0	**0**	0	0	0	0
Springfield	0	0	0	0	**0**	0	0	0	0

Note: Sums by SSF may not balance due to rounding.

Each facility's impact on non-interstate lane-miles is also shown for reference. Since each row in Table 3 represents the total shift in lane-miles throughout the state, the sum of all the values across each row should be approximately 0 (some are not 0 due to rounding). Based on the results, the Williston and Royalton SSFs have the greatest impact in terms of reducing overall distance to the nearest SLL. On the other hand, the SSF added to the Springfield garage service area has no impact on

reducing the distance of interstate lane-miles from the nearest SLL. The addition of the SSF in Springfield thus provides no travel-time benefits at all. Another way of explaining this finding is that even after the addition of a locally-optimal SSF, all of the roadway segments in its service territory are still closest to the garage, so the SSF makes no improvement. As shown in Figure 5, this phenomenon reflects the fact that the SSF was added very close to the garage, and that the garage is already situated very close to the interstates.

Figure 6 Garage and Satellite Salt Facility for the Springfield Service Territory

On the other hand, the Williston SSF, in the Colchester service territory, is far from the garage, in an ideal location for servicing the interstates (Figure 6).
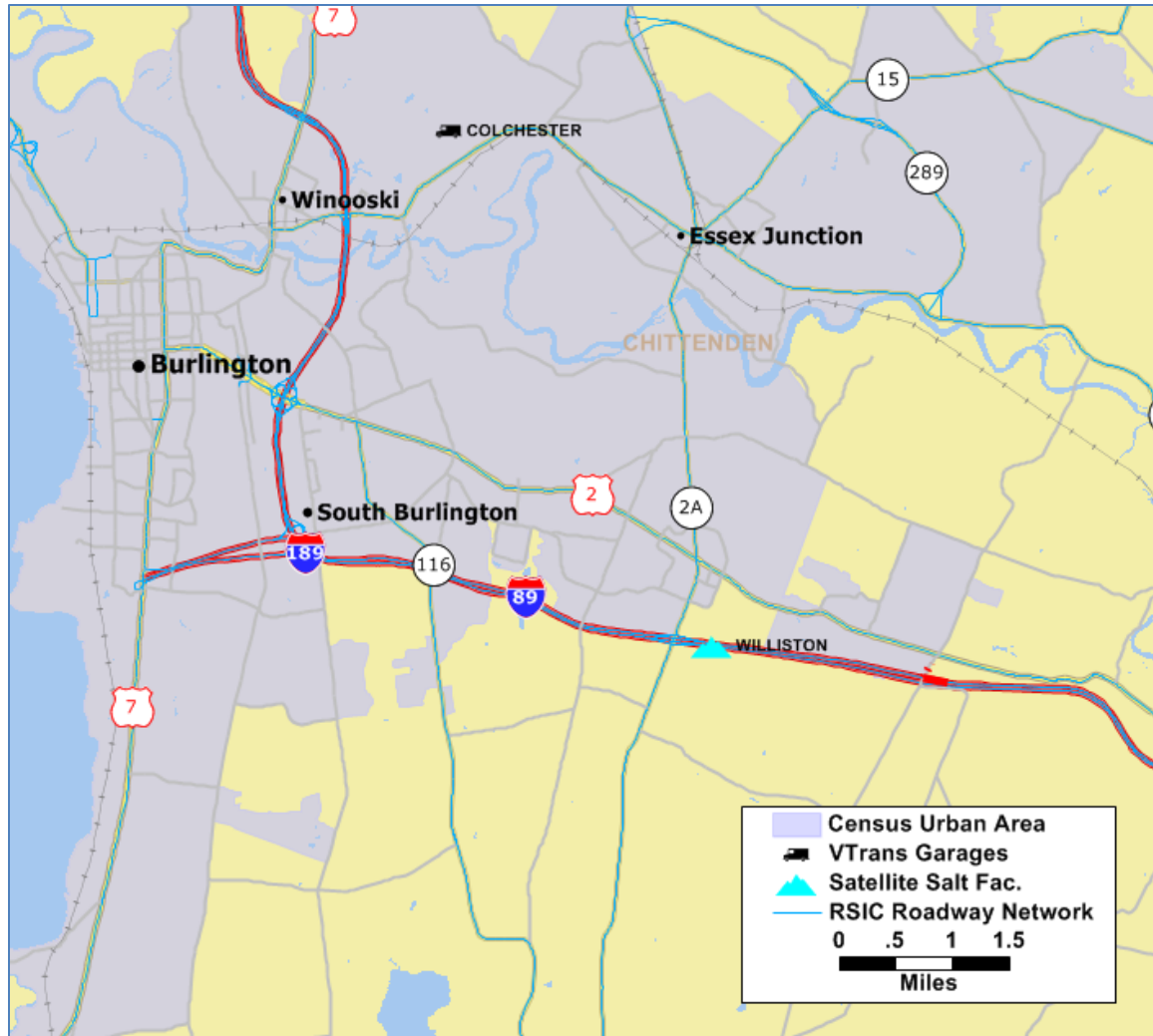
Figure 7 Garage and Satellite Salt Facility for the Colchester Service Territory

For the SSFs where "ties" exist – the reductions in travel-times below the 20-minute threshold are equal (for -3, -1, and 0 minutes in the "20+ column) – the reduction below the 10-minute threshold was used to resolve the tie.

The results further support the use of the 20-minute service-time threshold as a useful measure of performance for ranking SSFs. As shown in Table 3, using a 30-minute threshold would have resulted in a large number of ties in the ranking, since the addition of most of the SSFs had little to no effect on or above the 30-minute service time threshold. The 10-minute threshold would have resulted in a different rank ordering of SSFs if it was used as the performance threshold (Sheffield would have been #1 and Williston #2). However, using a 10-minute service time threshold to evaluate and rank the SSFs would ignore the substantial benefit provided by a reduction in lane-miles from the "20-<30" category into the "10-<20" category, as seen for the Royalton SSF (row 2 in Table 3). Salt loading becomes more of a binding constraint to RSIC operations as vehicles get farther from the nearest SLL, so setting a performance threshold that is too low is not particularly useful.

4.1.2 Non-Interstate SSFs

Table 4 shows the rank order for all non-interstate SSFs, along with the corresponding changes in lane-miles within each service time zone.

Table 4 Rank Order of Non-Interstate Satellite Salt Facilities

Satellite Salt Facility Location	Change in the number of non-interstate lane miles within the given time interval (in minutes to the nearest SLL)					
	<10	10 – <20	20 – <30	30 – <40	40 – <50	20+
Addison	15	25	-26	-13	0	-39
Bakersfield	11	25	-34	-2	0	-36
Orwell	24	11	-25	-7	0	-33
Cambridge	18	14	-30	-1	-1	-33
Jay	7	24	-18	-13	0	-31
Alburgh	25	5	-22	-8	0	-30
Middletown	9	21	26	-30	-25	-29
Pownal	13	15	-19	-9	0	-28
Manchester	13	13	-6	-1	-19	-26
Westmore	3	22	-16	-10	0	-26
Poultney	12	10	-1	4	-25	-22
Norton	22	-3	-19	-1	0	-20
Albany	10	10	-4	-12	-5	-20
Jamaica	15	4	-19	0	0	-19
Newfane	14	4	-19	0	0	-19
West Rutland	34	-16	-7	5	-16	-18
Cornwall	15	3	-13	-5	0	-18
Maidstone	5	13	-14	-4	0	-18
Troy	23	-6	-17	0	0	-17
Andover	16	0	-17	0	0	-17
Halifax	13	4	-14	-4	0	-17
Brunswick	11	4	-11	-4	0	-15
Topsham	10	5	-14	-1	0	-15
Pittsfield	3	12	-15	0	0	-15
Weathersfield	11	4	-14	0	0	-14
Barnard	8	5	-14	0	0	-14
Cabot	22	-9	-11	-2	0	-13
Brandon	14	0	-13	0	0	-13
Vershire	11	1	-12	0	0	-12
Eden	11	-2	-10	0	0	-10
Granville	5	5	-10	0	0	-10
Morgan	11	-3	-7	-1	0	-8
Whitingham	12	-5	-6	-1	0	-7
Fayston	5	0	-5	0	0	-5

| Satellite Salt Facility Location	Change in the number of <u>non-interstate</u> lane miles within the given time interval (in minutes to the nearest SLL)					
	<10	**10 – <20**	**20 – <30**	**30 – <40**	**40 – <50**	**20+**
Berlin	7	-3	1	1	-6	**-4**
Morristown	4	-1	2	-4	-1	**-3**
Chester	4	-2	-2	0	0	**-2**
Stamford	5	-5	0	0	0	**0**
Note: Sums by SSF may not balance due to rounding.						

The ranking is again based on the number of lane-miles shifted out of the greater than 20-minute travel-time zones and into the lower service-time zones. The SSF in the town of Addison is accessible by, and ideally situated for use by, the New Haven and Middlebury garages. Therefore, its cumulative effect on the network is significant, probably serving to reduce distances to the nearest SLL in all three of these service territories.

4.2 Operationally Feasible Sites for Locally-Optimal SSFs

Further analysis of the feedback received from the other states (Table 2) indicates that siting a SSF on a state-maintained roadway parcel might be more operationally feasible than the team had expected. Therefore, a final step in the siting of locally-optimal SSF locations was conducted, in an effort to find operationally feasible sites for some of the highly-ranked SSFs.

Respondents reported that many opportunities exist within the ownership parcel of the state-maintained road network for operationally feasible SSF locations. So the research team used Google Maps to look for sites which fit the criteria of what other states were already doing to site their own SSFs. These criteria include extra width in the right-of-way at interchanges and space within the inside shoulders of looped ramps at interchanges.

By applying these site-selection criteria, the team was able to align some of the locally-optimal SSF locations with operationally feasible SSF sites. For example, the locally-optimal Williston SSF, which was placed along the I-89 exit ramps for Vermont State Route 2A, is near extra space in the right-of-way between the ramps and the highway lanes, as well as between the divided-highway segments, at the turnaround south of the exit ramps. These feasible sites for an SSF are shown in yellow in Figure 8.
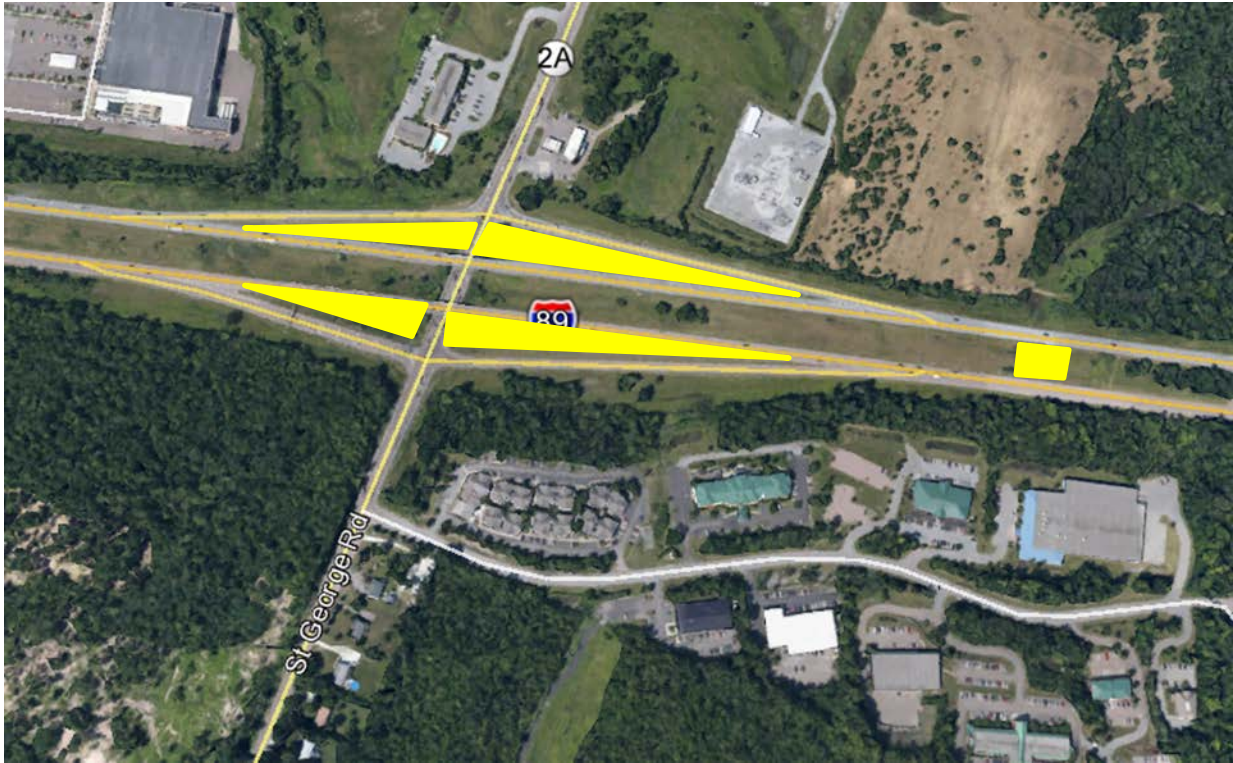
Figure 8 Aerial View of the Vicinity Around the Locally-Optimal Williston SSF

Survey respondents from both Wyoming and Kansas attested to using the extra width in the right-of-way as well as the insides of looped ramps at interchanges for satellite salt storage. Therefore, the vicinity of the Williston SSF shown in Figure 8 is well suited to be an operationally feasible SSF, with extra space in the right-of-way between the ramps and between the highway lanes themselves at a turnaround south of the exit ramps. Each of these potential areas is shown in yellow in Figure 8.

The Royalton interstate SSF was placed at a location on I-89 that was not close to any interchanges or ramps, but is close to an underpass with Oxbow Road (Figure 9).

Figure 9 Aerial View of the Vicinity of the Locally-optimal Royalton SSF

Further inspection of the aerial view reveals a denuded area around the underpass bridge, where service vehicles may already be leaving the travelled way to turn around or park. The area under this underpass may be able to serve as an operationally feasible site for this SSF.

The locally-optimal Brattleboro interstate SSF was placed at the I-91 interchange with U.S. Route 5. The vicinity of this SSF is also suited to an operationally feasible SSF, with extra space in the right-of-way between the ramps and the highway lanes themselves. Each of these potential areas can be seen in the aerial view in Figure 10.

Figure 10 Aerial View of the Vicinity of the Locally-Optimal Brattleboro Interstate SSF

The subset of locally-optimal, *non-interstate* SSFs tend to be more difficult to match to an operationally feasible location since the right-of-way on non-interstate roadways is typically smaller and more constrained than it is for interstate roadways. This constraint is particularly true for state-maintained roadways without limited access (with intersections). In these situations it may be necessary to follow the advice of several survey respondents to obtain easements or additional land to site SSFs adjacent to these roadways. For example, both North Dakota and Wyoming have obtained land easements or property acquisitions through their right-of-way programs, and often offset some of the property costs by providing fence-line improvements to the owner. These types of small scale public-private partnerships may be necessary if VTrans chooses to pursue additional SSF sites for non-interstate locations in Addison, Bakersfield, Orwell, Cambridge, and Jay.

At the intersection of State Routes 17 and 125 in Addison, where the locally-optimal non-interstate SSF was placed, opportunities for land acquisition may exist along the farmed properties lining the roadway (Figure 11).

Figure 11 Aerial View in the Vicinity of the Locally-optimal Non-Interstate SSF in Addison, Vermont

Along State Route 105 in Jay, there are a number of cleared patches of forest adjacent to the roadway which might serve as operationally feasible SSFs if the property could be obtained (shown hatched in white on Figure 12).

Figure 12 Aerial View in the Vicinity of the Locally-optimal Non-Interstate SSF in Jay, Vermont

In the words of the respondent from Wyoming, it may be necessary to get "as creative as we can without breaking the bank" in order to find suitable sites for these non-interstate SSFs.

4.3 Closed Rest Areas as Ready-to-Use SSFs

Since the only ready-to-use locations were determined to be the closed rest areas, the second approach considered these as SSFs, and evaluated them with the same evaluation method used for the locally-optimal SSFs. Table 5 provides the rank order of the four ready-to-use SSFs, along with the corresponding changes in lane-miles within each service-time zone.

Table 5 Rank Order of Ready-to-Use (Closed Rest Areas) Satellite Salt Facilities

Rest Area Location	Change in the number of lane miles within the given time interval (in minutes to the nearest SLL)								
	Interstate lane miles					Non-interstate lane miles			
	<10	10-<20	20-<30	30-<40	20+	<10	10-<20	20-<30	30-<40
Sharon	17	1	-18	0	**-18**	4	4	-8	0
Randolph	8	-7	-2	0	**-2**	0	0	0	0
Highgate	16	-16	0	0	**0**	10	-10	-1	0

	Change in the number of lane miles within the given time interval (in minutes to the nearest SLL)								
Rest Area Location	Interstate lane miles					Non-interstate lane miles			
	<10	10-<20	20-<30	30-<40	20+	<10	10-<20	20-<30	30-<40
Hartford	7	-7	0	0	**0**	0	0	0	0
Note: Sums by SSF may not balance due to rounding.									

Both the Sharon and Randolph closed rest areas would reduce the number of interstate lane-miles greater than 20 minutes from a SLL, but the reduction provided by the Sharon facility would be significant. In fact, measured against the locally-optimal interstate SSFs in Table 3, the Sharon rest area ranks as the 5th most effective satellite facility. Since the operational feasibility of this facility has been assumed, it makes sense for it to be included in the RSIC network as an SSF.

4.4 Sizing of Satellite Salt Storage Facilities

Additional information was received through the AASHTO Listserv regarding appropriate ways to size salt storage facilities. For salt storage at garages, this sizing may not be important since excess capacity is likely to be available. However, new satellite facilities will benefit from a method dictating the maximum capacity needed so that an appropriately-sized enclosure can be obtained.

Steve Otto of Alberta, Canada (personal communication, April 11, 2014) reported that they specify salt "shed" capacity as 45% of the 5-year average expected annual usage for that shed, or 200 tons, whichever is greater. The intent here is to have enough salt for about one month of RSIC operations.

Thomas Lyden of the Ohio DOT (personal communication) reported that they began sizing new structures by calculating the expected rolling 30-day salt-usage in tons throughout the winter season (November 1 to April 1) for the site. The size of the shed then is calculated as the average of these values plus 1.96 standard deviations, ensuring with 95% confidence that the structure holds enough salt for 30 days even if no new salt shipments are possible. The goals of these methods are similar.

For new SSFs, it will be necessary to make some assumptions about the expected salt usage in order to estimate the capacity needed for sizing the facility. The project team recommends assembling the 5-year usage for each of the garages expected to make use of the facility, then using a fraction of the averages between all of the garages. The fraction used can be based on the percent of the total vehicle-hours of travel (VHTs) incurred by all of the routes using these garages originally that is will be occupied by the routes using the SSF. This percentage can be calculated by optimizing the RSIC routes with and without the SSF using the routing routine developed previously (Dowds et. al., 2013).

5 Conclusions and Future Work

A viable novel method has been developed to identify and rank SSFs for the distributed system of garages which serves to promote effective improvements to RSIC services by VTrans. The method identifies a locally-optimal locations for each existing service territory, then evaluates and ranks their benefit to the network as a whole, in terms of the total lane-miles of state-maintained roadway shifted under the 20-minute service-time threshold.

These locally-optimal SSFs will best serve the state's RSIC operations by being sited near or on interstate highways, within the existing right-of-way. The most effective locations are in Williston at the interchange of I-89 and State Route 2A, in Royalton at the underpass with Oxbow Road, and in Brattleboro at the interchange of I-91 and U.S. Highway 5. The Sharon rest area is a ready-to-use, operationally feasible SSF that could begin to offset RSIC costs immediately.

The critical aspect to siting new SSFs will be the ability to utilize existing right-of-way around the interstates creatively and to explore partnerships will other landowners adjacent to the state highway right-of-way who may be willing to sell a small portion of cleared land for use as an SSF.

Future research could explore how new interchange design can incorporate salt storage within the right-of-way, since interstate interchanges frequently appear as ideal locally-optimal SSF locations. The evaluation method described in this paper can be used to justify not only the placement of SSFs, but also the construction costs for new salt, brine, and sand facilities by calculating the RSIC fleet service time improvements that will result from individual SSFs.

As described previously, the procedure used to evaluate the effectiveness of the SSF locations in this project could be further automated to optimize pairs and triples of locally-optimal SSF locations. An automated tool with augmented computing power will be needed because this type of location problem involves running hundreds of thousands of iterations of the SSF location tool. Alternatively, different heuristic solutions could be explored, which sequence the addition of new SSFs one-at-a-time by optimizing the lane reductions across the entire network, and considering the statewide benefit of each facility individually. An interesting research goal would be to compare the outputs of such a procedure to identify 60 new optimized SSFs with the outputs of the project described here.

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