Quantifying the Impact that New Capital Projects Will Have on Roadway Snow and Ice Control Operations

Transportation Research Center
University of Vermont

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In recent years, many states have experienced heavy burdens on their snow and ice control budgets. Increases in winter/spring precipitation results in increased costs to state DOTs for winter roadway maintenance materials (salt, sand, chemicals, etc.), plow operator time, equipment maintenance and replacement budgets, and fuel use. As state DOTs adjust to climate conditions that include not only more precipitation, but more severe and unpredictable weather events, it will become increasingly important to integrate the cost of roadway snow and ice control (RSIC) operations into their capital-project planning processes. The overall goal of this project was to support state DOTs' operations & maintenance efforts by developing an automated method for quantifying the expected impact that new capital projects will have on RSIC operations.

The effects of a new suburban roadway were found to be the most significant, requiring 266 vehicle-minutes of travel along with almost 40 minutes of additional service time or one additional fleet truck for each mile of new roadway. The results and findings of this research have implications for short-term funding allocations for RSIC operations staff and for long-term consideration of RSIC in the highway planning and design processes. The findings of this project provide defensible data for operations staff to advocate for increases in funding to offset the increased RSIC burden when a project is completed. The calculation tool created incorporates all of the results above into a MS Excel decision support platform, providing quick estimates of the monetary impact of a variety of major highway project types.

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Quantifying the Impact that New Capital Projects Will Have on Roadway Snow and Ice Control Operations

FINAL REPORT

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LIST OF ABBREVIATIONS

AASHTO – American Association of State Highway Transportation Officials

DOT – Department of transportation

GIS – geographic information system

GPS – global positioning system

HS – high-salt

LS – low-salt

NRI – Network Robustness Index

RSIC – Roadway snow and ice control

STIP – Statewide Transportation Improvement Program

TAZ – traffic analysis zone

USDOT – United States Department of Transportation

VHT – vehicle-hours of travel

EXECUTIVE SUMMARY

In recent years, many Snow Belt states have experienced heavy burdens on their RSIC budgets due to an increase in extreme winter weather. Increases in winter/spring precipitation will result in increased costs to state DOTs for winter roadway maintenance materials (salt, sand, chemicals, etc.), increased plow operator time, increased equipment maintenance and replacement budgets, and increased fuel use. As state DOTs adjust to climate conditions that include not only more precipitation, but more severe and unpredictable weather events, it will become increasingly important to integrate the cost of RSIC operations into their capital-project planning processes. The introduction of new capital projects will obviously result in additional costs to state DOTs, as new projects increase the total effort and expenditure needed for RSIC operations. It is the case; however, that the additional RSIC operations and maintenance burden associated with new capital projects is rarely, if ever, quantified and is therefore typically not considered during the early stages of the capital-project development process.

The overall goal of this project was to support state DOTs' operations & maintenance efforts by developing an automated method for quantifying the expected impact that new capital projects will have on RSIC operations. The suggested approach emphasizes the need to explicitly consider RSIC-based costs in the transportation project prioritization and climate adaptation planning processes, as RSIC operations pose a large annual cost for many states.

The following table contains a summary of the results of the Integrated RSIC Model applications and the GPS data collection for the increase in effort measured as increase in the total vehicle-minutes of travel for each pass.

Project Type	Quantity	Unit	Region Type	Low-Salt Storm	High-Salt Storm	Average Unit Increase (min.)	
New roadway, 1-lane either direction	0.55	miles	suburban	168	125	**266**	**per mi.**
New roadway, 1-lane either direction	3.56	miles	urban	182	411	**83**	**per mi.**
New left-turn lanes, 2 of 4 approaches	2	approach	rural	245	248	**123**	**per approach**
New roadway, 1-lane either direction	3.26	miles	rural	-48	-175	**-34**	**per mi.**
Highway lane addition, from 1 to 2 in both directions	9.20	miles	rural	356	63	**23**	**per mi.**
Conversion of stop- and yield-controlled intersection to a roundabout	1	each	rural	-1	8	**4**	**per intx**

For each of these applications, the number of vehicles was held fixed, so the results assume that no new vehicles (trucks or tow-plows) are added to the RSIC fleet. The effects of the new suburban roadway were the most significant, as expected since the road network is less connected outside of the urban core and there are fewer opportunities to devise an alternative set of efficient routes with the new roadway. Adding left-turn lanes to a rural intersection approach also had a significant effect on RSIC effort. These types of intersection improvements are common in rural and suburban areas where right-of-way is available for the addition of turning lanes, but their considerable effect on RSIC effort must be considered, especially in relation to the more moderate effect of converting a rural intersection to a roundabout.

The following table contains a summary of the increase in vehicles allocated to the garage where each project is located.

Project Type	Quantity	Unit	Region Type	Low-Salt Storm	High-Salt Storm	Average Unit Increase (trks)	
New roadway, 1-lane either direction	0.55	miles	suburban	1	0	**0.91**	**per mi.**
New roadway, 1-lane either direction	3.56	miles	urban	1.5	1	**0.35**	**per mi.**
New left-turn lanes, 2 of 4 approaches	2	approach	rural	0.5	0.5	**0.25**	**per approach**
New roadway, 1-lane either direction	3.26	miles	rural	1	1	**0.31**	**per mi.**
Highway lane addition, from 1 to 2 in both directions	9.20	miles	rural	1	2	**0.16**	**per mi.**
Conversion of stop- and yield-controlled intersection to a roundabout	1	each	rural	--	--	**1***	**per intx**

As with the measured increases in effort, the effects of the new suburban roadway were the most significant, requiring almost 1 additional truck for each mile of new roadway. Lane additions were shown to have less of a need for additional trucks. Unless the new turn lanes are close to a garage, having a new vehicle deadheading through the network to reach the new lanes will rarely be efficient. Although the field data analysis was not able to identify the potential need for additional vehicles, it is possible that a roundabout will require a new vehicle simply because its configuration precludes the use of some heavier trucks.

The following table contains a summary of the increase in service time on the network, or the time it will take to complete a single pass across all state-maintained roadways.

Project Type	Quantity	Unit	Region Type	Low-Salt Storm	High-Salt Storm	Average Unit Increase (min.)	
New roadway, 1-lane either direction	0.55	miles	suburban	8	35	**39**	**per mi.**
New roadway, 1-lane either direction	3.56	miles	urban	9	38	**7**	**per mi.**
New left-turn lanes, 2 of 4 approaches	2	approach	rural	14	0	**4**	**per approach**
New roadway, 1-lane either direction	3.26	miles	rural	12	0	**2**	**per mi.**
Highway lane addition, from 1 to 2 in both directions	9.20	miles	rural	5	16	**1**	**per mi.**
Conversion of stop- and yield-controlled intersection to a roundabout	1	each	rural	--	--	**0**	**per intx.**

As with the other measures of RSIC burden, the effects of the new suburban roadway were the most significant, requiring almost 40 minutes of additional service time for each mile of new roadway. The other projects were shown to have a minimal effect on service time, especially in the high-salt storm scenario, when the longest service time was likely to have been at a garage that was elsewhere on the network, so the statewide service time did not change.

The results and findings of this research have implications for short-term funding allocations for RSIC operations staff and for long-term consideration of RSIC in the highway planning and design processes. The findings of this project provide defensible data for operations staff to advocate for increases in funding to offset the increased RSIC burden when a project is completed. The calculation tool created incorporates all of the results above into a MS Excel decision support platform, providing quick estimates of the monetary impact of a variety of major highway project types.

These findings also provide a strong argument for the increased need to involve RSIC operations staff in the highway planning and design processes for major capital projects. The ultimate long-term goal is for the geometric design of highways to fully consider the impacts on all operations & maintenance needs, including RSIC.

CHAPTER 1: INTRODUCTION

Over the last 50 years, precipitation has increased substantially in much of the United States. This increase is clearly illustrated in Figure 1, from the Third National Climate Assessment Report (2014). According to the Report, the increase in precipitation will continue into the foreseeable future. Consequently, winter precipitation events (snow, ice, freezing rain, etc.) are expected to increase in many of the states which already experience substantial precipitation in the winter and spring seasons. This trend will most likely translate into increased roadway snow and ice control (RSIC) costs for many of those states – especially those in the Northeast and northern Midwest.

In recent years, many Snow Belt states have experienced heavy burdens on their RSIC budgets due to an increase in extreme winter weather. For example, in 2014, the entire fiscal year operating budget for all of the New Jersey Department of Transportation was exceeded by 200% on winter RSIC alone (R. M. Shaw, personal communication, March 2, 2014). Intuitively, increases in winter/spring precipitation will result in increased costs to state DOTs for winter roadway maintenance materials (salt, sand, chemicals, etc.), increased plow operator time, increased equipment maintenance and replacement costs, and increased fuel use. As state DOTs adjust to climate conditions that include not only more precipitation, but more severe and unpredictable weather events, it will become increasingly important to integrate the cost of RSIC operations into their capital-project planning processes.

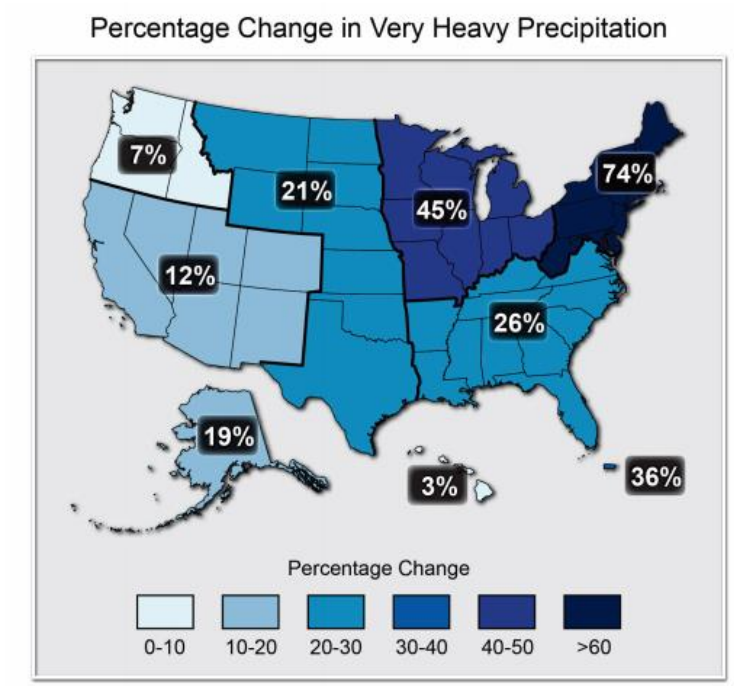


Figure 1 Percentage Change in Very Heavy Precipitation (from the Third National Climate Assessment Report, 2014)

Many of the affected states are already facing substantial budget constraints and make sacrifices to adequately maintain the existing roadways with respect to RSIC operations. The completion of new capital projects will often result in additional costs to state DOTs, as new projects that add lanes miles increase the total effort and expenditure needed for RSIC operations. Additional RSIC operations and maintenance burden associated with new capital projects is rarely, if ever, quantified and is therefore typically not considered during the early stages of the capital-project development process. As a result of this oversight, the Operations Divisions in DOTs with substantial RSIC responsibilities may find themselves without the necessary resources or budget to adequately maintain their federal-aid roadway network in winter/spring months. In turn, this can have a negative impact on both safety and mobility within those states.

1.1 GOALS OF THE PROJECT

The overall goal of this project was to support state DOTs' operations and maintenance efforts by developing an automated method for quantifying the expected impact that new capital projects will have on RSIC operations. The suggested approach emphasizes the need to explicitly consider RSIC-based costs in the transportation project prioritization and climate adaptation planning processes, as RSIC operations pose a large annual cost for many states. For this project, we examined two general categories of new capital projects to assess their impact on RSIC operations:

- Additions of new roadway capacity including new lanes, new shoulders, as well as new roadway builds
- New roadway configurations such as new striping plans, new curb-cuts, new bulb-outs, bike lanes, etc.

The research team developed a methodological approach to quantify the impact that new capital projects will have on total vehicle-hours of travel (VHTs) and equipment needs for the RSIC fleet.

1.2 BACKGROUND

The team extended an existing RSIC allocation and routing tool that was developed in a previous project funded by VTrans into a fully Integrated RSIC Model. The current tool is used to plan the most effective routes for a RSIC fleet by minimizing total operating hours and fuel. It can also provide RSIC service according to a roadway prioritization hierarchy (i.e., serving the highest priority roadways first). For this project, the team expanded the functionality of the tool by integrating it with a travel model and a tool for calculating the criticality of network links.

The importance of developing an integrated model to understand the effects of a new roadway configuration comes from a need to better understand the "ripple" effects that an increase in a fleet's RSIC burden can have. The localized impact of a new capital project might include the need for a specific driver to spend more time providing service to a new roadway segment, or an existing roadway segment that has been changed, or the need for a different piece of equipment to provide service when a change has been made. However, these changes will not only affect that specific driver and their route, but are likely to impact the rest of the district, and the entire RSIC fleet. It is likely that changes will need to be made to other routes to equalize the RSIC burden and continue to provide services in an efficient manner. It is also possible that RSIC vehicles will need to be moved from one district to another to meet the new demand caused by different capital projects. The indirect "ripple" effects throughout the state's network can be the most substantial costs resulting from a new roadway configuration, so it is critical that they be considered.

1.2.1 Statewide Travel Model

Travel models are detailed GIS-based planning tools that can be used to provide projections of everyday travel-behavior under a variety of scenarios for transportation planning studies, such as adding a new capital project to the federal-aid roadway network. The outputs provided by these models are used to facilitate accurate and timely travel forecasts as well as to gain a better understanding of the current operational status of existing transportation systems, which helps direct funding and policy decisions.

Vermont's statewide travel model is a series of spatial computer processes that use land-use and activity patterns to estimate travelers' behaviors on a typical day. Origin and destination tables are created, describing the number of expected trips between traffic analysis zones (TAZs). Accommodations are made for commercial-truck trips and the occupancy characteristics of passenger vehicles. The final outputs are traffic volumes by roadway link on the statewide federal-aid roadway network. The Vermont Travel Model currently includes 936 TAZs and 5,327 miles (see Figure 2).

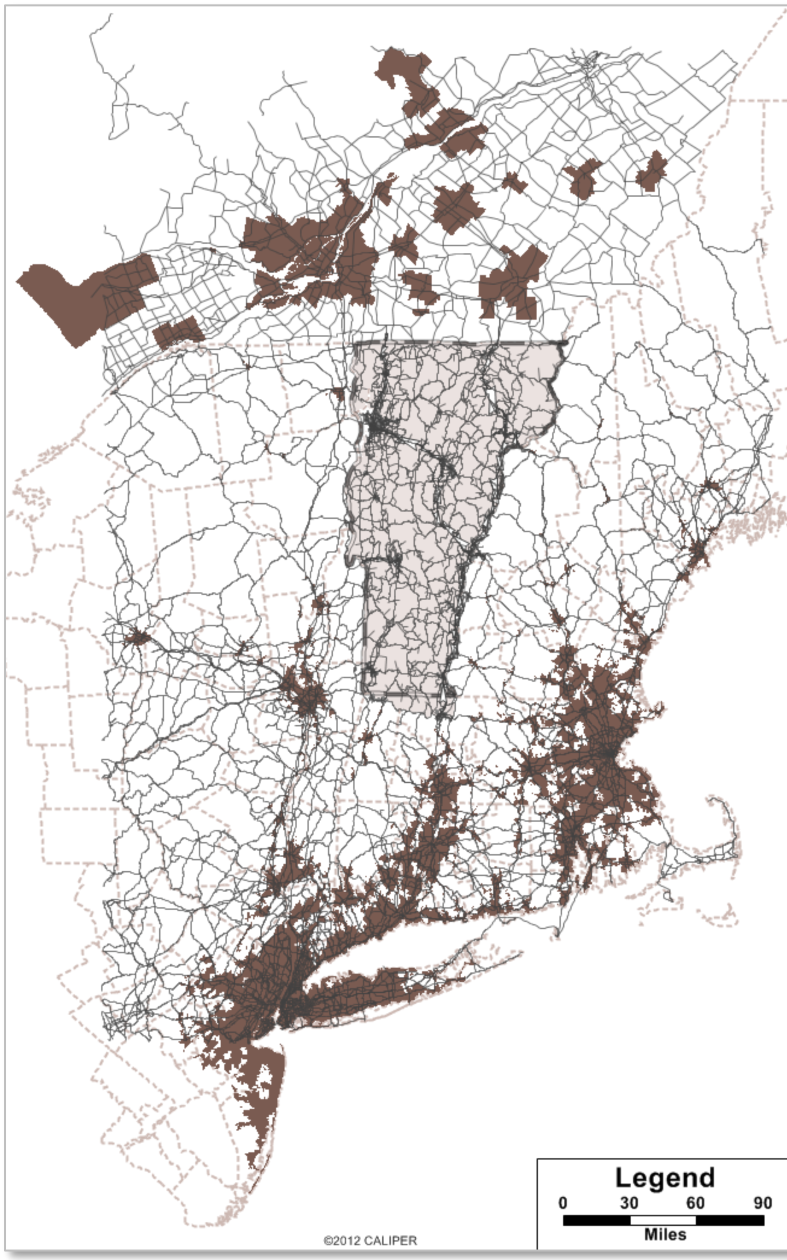


Figure 2 Zones and Road Network in the Vermont Travel Model

1.2.2 The Network Robustness Index (NRI) Calculation Tool

The Network Robustness Index (NRI), is a performance measure for evaluating the importance of a given roadway segment (i.e., network link) with respect to the entire roadway network. The NRI is based on the change in travel-times associated with re-routing all traffic in the network when a given roadway link becomes unusable. Thus, the most important links in the network are the links: 1) that carry a relatively high volume of traffic, and 2) lack nearby alternative routes. The algorithm for the NRI tool was first developed in 2006 and it now allows the decision maker to differentiate the importance of different types of vehicle trips by trip purpose, and is used to rank-order all links in the transportation network.

1.2.3 The RSIC Allocation & Routing Tool

The existing RSIC allocation and routing tool utilizes an innovative procedure for finding optimal routes for a given fleet of RSIC vehicles, ensuring that each vehicle is utilized and total vehicle-hours of travel are minimized. The procedure starts with a network that has been clustered into districts, and proceeds by assigning each vehicle in the fleet to a district. This vehicle-allocation step is repeated after each routing step so that none of the fleet is left idle (see Figure 3).

Each of the sub-components of the Integrated RSIC Model is built on the TransCAD® software platform. TransCAD® is a Geographic Information System (GIS) designed specifically to store, display, manage, and analyze transportation data. TransCAD® integrates GIS and transportation modeling into a single platform, providing capabilities in mapping, visualization, and analysis with application modules for routing, travel-demand forecasting, public transit, logistics, site location, and territory management.

1.3 REPORT SUMMARY

Chapter 2 of this report identifies and describes all of the data collected and used in this project. Section 3 provides a detailed description of the methods used to analyze data, including the development of the Integrated RSIC Model and the Calculation Tool. Chapter 4 provides a summary of the results of those analyses, and the application of the Integrated RSIC Model. Chapter 5 provides the conclusions of the project and the recommendations for how those conclusions can be used to influence the way that capital projects are developed.

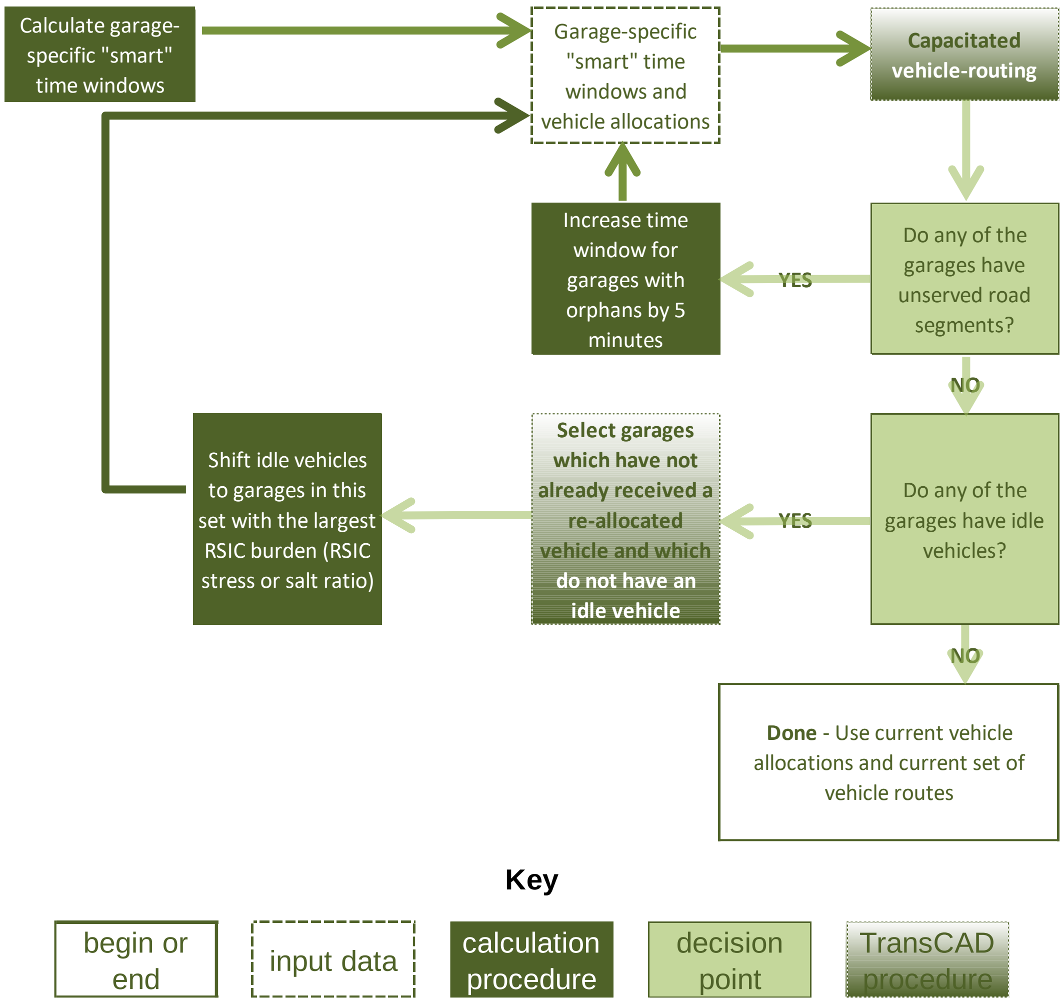


Figure 3 Iterative Procedure for RSIC Allocation & Routing

CHAPTER 2: DATA USED IN THIS PROJECT

This section describes the data that was collected or gathered from other sources during the execution of this project.

2.1 SURVEY DATA COLLECTION AND SELECTION OF CASE STUDIES

The first project task involved the preparation and distribution of a survey to decide on the types of projects to be studied. The purpose of the survey was to solicit information on project types that are common across the Clear Roads' member states and which cause concern for RSIC burden. The survey was distributed to the AASHTO RSIC ListServ in an email with the following text:

> *We are in the beginning stages of a project funded by the Clear Roads research program that is aimed at measuring the increased burden on snow and ice control (SIC) that results from new roadway configurations or expansions. We intend to examine 6-10 "case studies" featuring typical roadway projects that have an effect on the effort or equipment required for SIC. An example would be changing a traditional signalized intersection into a roundabout. We will measure the effort required before and after the new configuration has been completed.*
>
> *What we need are case studies to focus on in the 2016 construction season, so that we can observe "before" conditions this winter season. So if you know of a project that is being built or implemented in 2016 that is a concern for SIC, let us know! Also, let us know if there is a general type of project that concerns you, even if you don't know of one being implemented in 2016.*
>
> *Ideally, we would like to observe the pre- and post- implementation conditions first-hand, but if your fleet stores historical AVL data, we may be able to use that to measure the effort required for a project that has already been completed. So also let us know if your agency logs and stores historical AVL data from your SIC fleet, even if it's only last winter.*
>
> *Any input you can provide would be greatly appreciated.*

The email responses received are compiled in Appendix A.

After following up on the projects suggested by the survey responders, it became clear that detailed information on the full array of capital projects that suited the needs of this research was limited. Therefore, it was very difficult for RSIC managers to identify capital projects with construction scheduled in 2016 that would be completed by the winter of 2016/2017. Therefore, the investigation of potential capital projects to use as case studies was shifted from the survey responses to a scan of the State Transportation Improvement Programs (STIPs) for a subset of the Clear Roads member states represented by the responders. The STIP is a staged, multi-year, statewide, intermodal program of capital projects, funded by the USDOT. Federal requirements dictate that the STIP must cover a period of not less than 4 years, it must be fiscally constrained by year and include financial information to demonstrate which projects and project phases are to be implemented using yearly revenues.

STIP projections for 2016-2019 were scanned for projects with significant (> $10,000) construction scheduled in FY2016 and no further construction planned in FY2017. The types of projects sought were lane additions, roadway expansions (including complete streets and bike lane additions), roundabouts, and bridge reconstructions. The case study investigation was focused on the states which responded to the initial survey:

- Indiana
- Minnesota
- New Hampshire
- Maine
- Vermont

For Indiana, 17 possible capital projects were initially found which included added travel lanes, bridge widening, and an intersection improvement with a roundabout. However, none of these projects could be confirmed to be starting in FY2016 and completed by FY2017.

For Minnesota, 67 possible capital projects were initially found consisting of bridge replacements, shoulder paving/widening, bike/ped improvements, and added turn lanes. From these, two candidates for case-study analysis were selected because they seemed to fit the constraints of the project:

- MN 25/55: Reconstruction, widening, signalization, and addition of left-turn lanes at the intersection of MN 25 & MN 55 and construction of a roundabout at the intersection of MN 25 and 8^{th} St. in Buffalo
- MN 371: Four-lane expansion (from one lane in each direction to 2 lanes in each direction) of MN 371 in Nisswa, Pequot Lakes, and Jenkins

For New Hampshire, 12 possible capital projects consisting of roadway widening (additional lanes), addition of bike shoulders, bridge replacement, roadway reconstruction, and roundabout construction. From these, two candidates for case-study analysis were selected:

- NH 108: Reconstruction of the roadway and addition of bike shoulders on NH 108 in Durham and Newmarket
- NH Roundabout: Construction of a roundabout at the intersection of US 2 and US 3 in Lancaster

For Maine, the STIP was reviewed but the review did not uncover any new types of capital projects that were not already covered by projects found in other states.

For Vermont, the STIP review only revealed 10 capital projects. In Vermont, extensive capital costs are still being dedicated to repairs from Hurricane Irene. None of the projects investigated for Vermont was scheduled to be completed by FY2017, but construction timing was not critical for Vermont because a the Integrated RSIC Model was to be used. Therefore, the following 3 projects were selected for analysis using the Vermont Integrated RSIC Model:

- CrCo: Construction of a new by-pass roadway (the Crescent Connector) between State Route 2A and State Route 117, with improvements to Railroad St. between State Routes 15 and 117 in Essex Junction
- Rt2Lefts: Construction of new left-turn lanes for US Route 2 traffic at its intersection with Clay Point Road / Bear Trap Road in Colchester
- ChPa: Construction of a new roadway (the Champlain Parkway) from I-189 to Lakeside Ave. in Burlington. The Champlain Parkway, formerly the 'Southern Connector' originated in the 1960's as a 4-lane, limited access highway to improve vehicular access between downtown Burlington and I-89. Today's 2-lane version, with a multi-modal design that includes significant stormwater, bike/pedestrian, and traffic calming components, represents a fundamental departure from the project's distant origins.

Figure 4 shows the locations of the initial seven case-study capital projects selected for analysis.

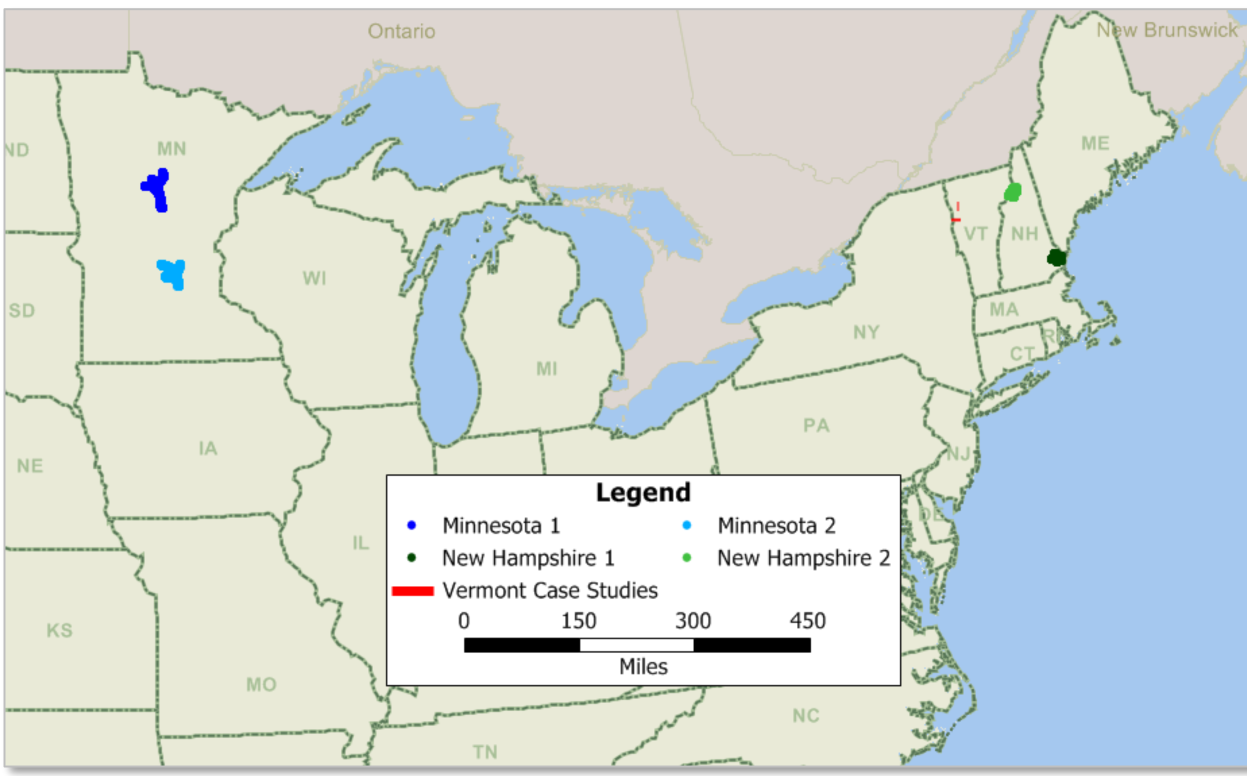


Figure 4 Locations of initial seven capital projects selected for case studies

An additional set of Vermont projects were selected as "reserve" case studies. These case studies were chosen so that they could be used in case any of the other projects failed to obtain valid field data. With the collection of field GPS data, there is always a risk that projects will not yield usable data. So the following projects were held as “reserve” case studies:

- The Southern Segment of the Bennington ByPass (BennBP): The proposed bypass of Bennington originated in the 1950's and was studied for several decades as a complete bypass of downtown Bennington, primarily for tourists wishing to access the ski areas east of Bennington. The 4.2-mile Western Segment, stretching from Hoosick, NY westward to Route 7, was completed in 2004. The Northern Segment, linking US Route 7 with State Route 9 to the east of town, was completed in 2014. The third and final segment is the Southern Segment, which will extend in an arc from Route 9 southwest to Route 2.

- Resurfacing of State Route 100 between Waterbury and Stowe, Vermont, beginning at the US Route 2 intersection and extending to the north 9.8 miles (Rt100LaneAdds): Although this project does not include a lane expansion along its entire scope, it does include capacity improvements and some Vermont residents have argued that it should also include a full lane expansion, due to congestion problems related to winter tourism. Therefore, a multilane expansion is envisioned here as a potential case study.

2.2 GPS DATA COLLECTION

For each of the case studies outside of Vermont, the truck responsible for servicing the roadway affected by the construction was instrumented with a GPS device, the GeoStats GeoLogger, to obtain detailed information on the effort required to service it, both before and after the construction project. GPS devices were mailed to the district supervisors to put into the trucks where these projects would be built for the winter of 2015-2016, then again for the winter of 2016-2017.

After the 2015-2016 winter, the GPS data were plotted and mapped to check their quality upon the return of the devices. Data logged by the GPS devices were available for download using the download utility provided by GeoStats (Figure 5).

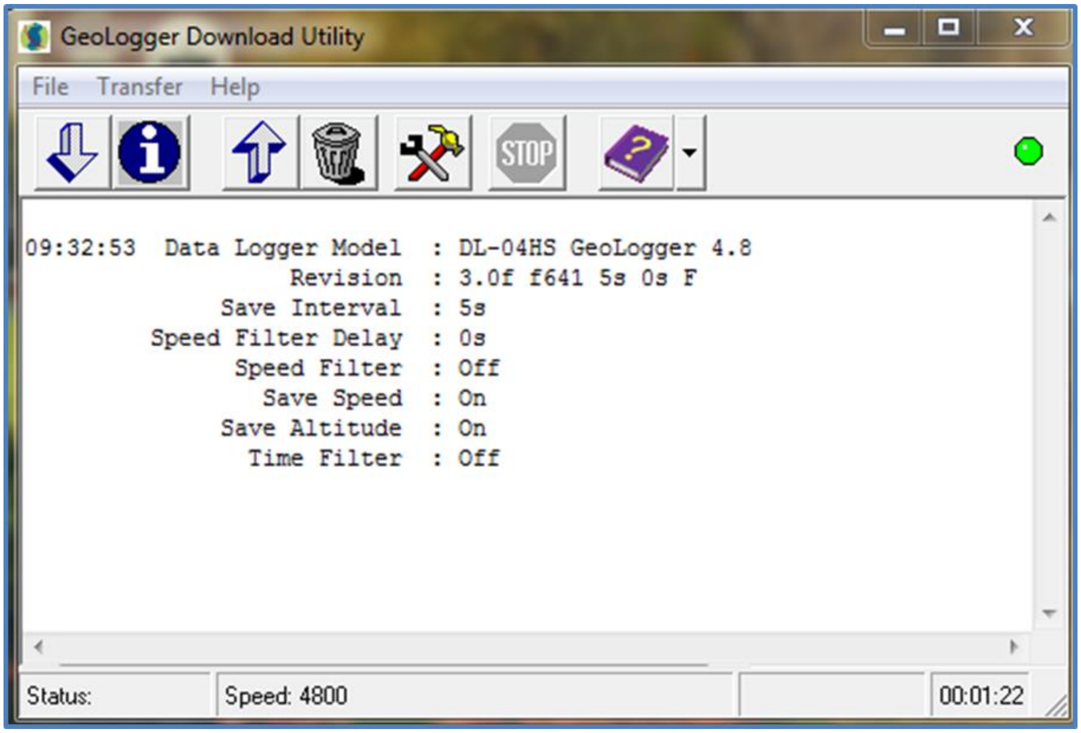


Figure 5 GeoStats Download Utility

The “Save Interval” was set at 5 seconds, indicating that a GPS point would be logged every 5 seconds while the vehicle was turned on. Although the device is capable of saving at 1-second intervals, 5 seconds was deemed sufficient for this study, and would ensure that a full winter of data could be stored on the device. All data recorded to the GeoLogger were downloaded in a single file, containing the following fields:

- Latitude – Latitude of the vehicle position
- Longitude – Longitude of the vehicle position
- Time – clock time (00:00:00)
- Date
- Speed – vehicle speed, in miles per hour
- Heading – direction of travel (0 to 360 degrees)
- Altitude – Altitude of the vehicle (feet above mean sea level)
- HDOP – horizontal dilution of precision, an indication of the quality of the lat/long results

- Satellites – the number of satellite signals contributing to the GPS point

In all four cases for the 2015-2016 winter, the data were found to be effective, and their spatial representation coincided perfectly with the expected route that the vehicle was servicing. Figure 6 provides an example of the plotted GPS data for the project on MN 371 in Minnesota. The inset of Figure 6 verifies that the route indicated consists of many individual GPS points corresponding to the truck's position every 5 seconds.

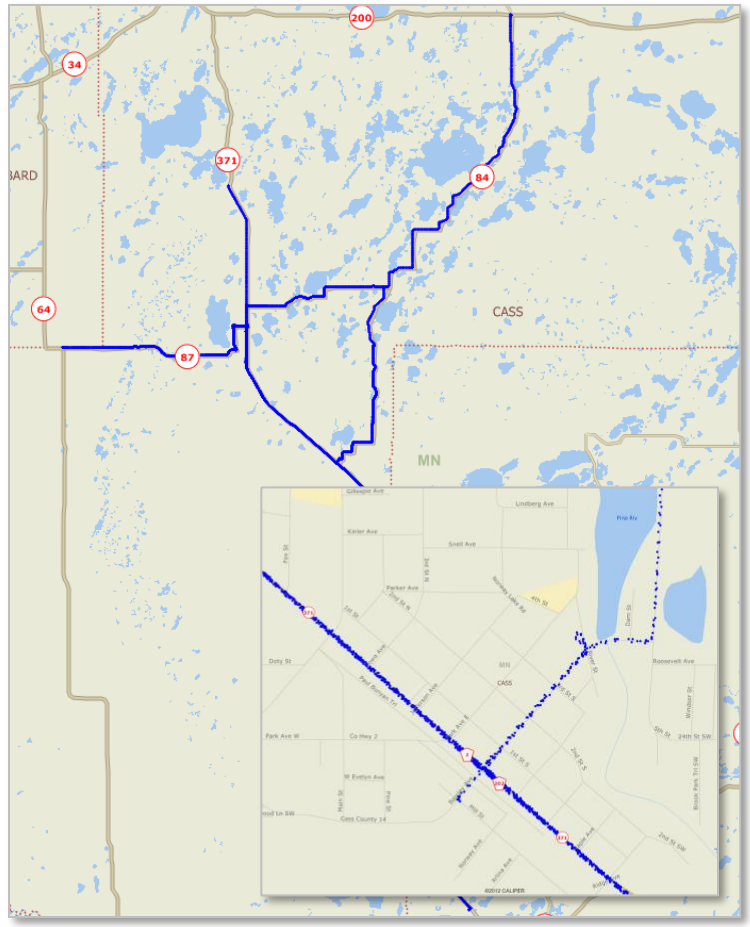


Figure 6 GPS data for the MN 371 Project in Nisswa, Pequot Lakes, and Jenkins, Minnesota

Upon return of the GeoLogger devices after the winter 2016-2017 data collection, it was discovered that three of the four devices contained no data, making the use of these case studies for analysis in this project impossible. After reviewing the procedures for shipping, installing, and returning the devices, it was determined that the most likely cause of the data deletion was contact with magnetic fields during return shipping. Since the GeoLogger stores all of its data in flash memory, contact with, or proximity to, a magnetic device causes loss of data. Unfortunately, the GeoLogger's own antenna unit itself is magnetic (Figure 7).

In turn, this means that keeping the antenna separated from the logger during shipping is critical. An envelope-type mailer was used for return shipping for the first winter data collection, making contact between the antenna and the logger difficult. However, due to problems with the postage requirements for the envelope-type mailer, a larger box-type mailer was used for return shipping for the second winter data collection event. The box-type mailer allowed the antenna and the logger to move around more freely within the package.

Figure 7 GeoStats GeoLogger (l. to r.) datalogger, 12V adapter, and antenna

Therefore, only one of the four case studies yielded usable data for both winter data collection periods. This case study was the replacement of a traditional stop- and yield-controlled intersection at US 2 and US 3 in Lancaster, New Hampshire (Figure 8a) with a roundabout (Figure 8b).

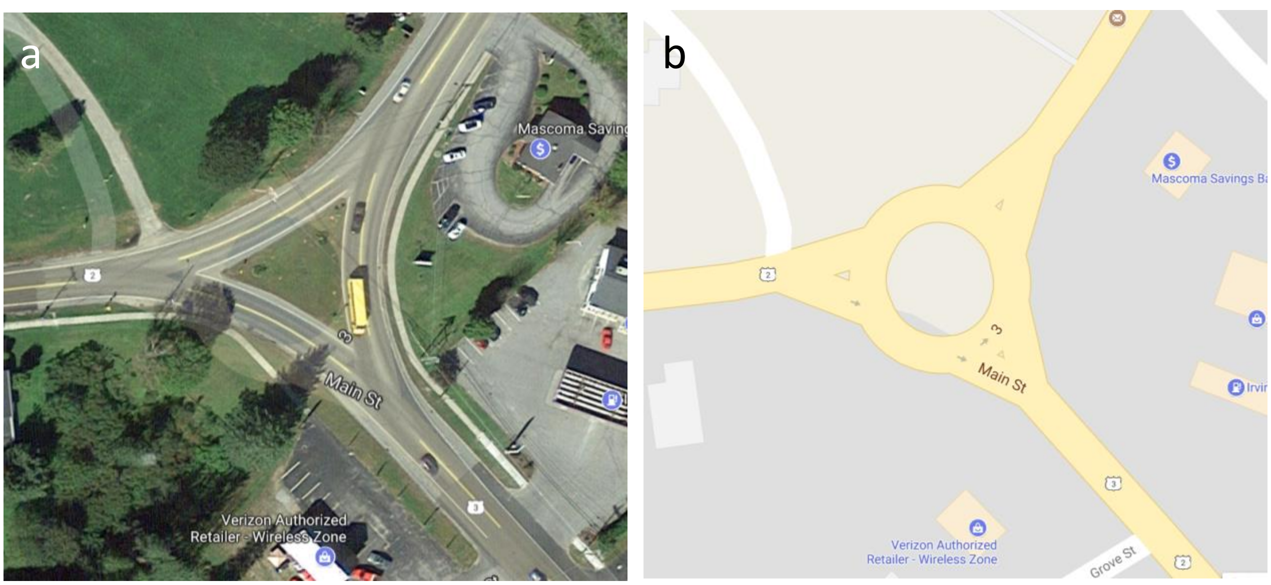


Figure 8 The intersection of US 2 and US 3 in Lancaster, New Hampshire as a stop- and yield-controlled intersection (a) and as a roundabout (b)

Figure 9 shows the GPS data corresponding to the RSIC service before (green) and after (blue) the project had been completed supports the new traffic pattern created by the roundabout, especially in the southwest edge of the roundabout, where the right-of-way had to be significantly extended to accommodate the new circular geometry.

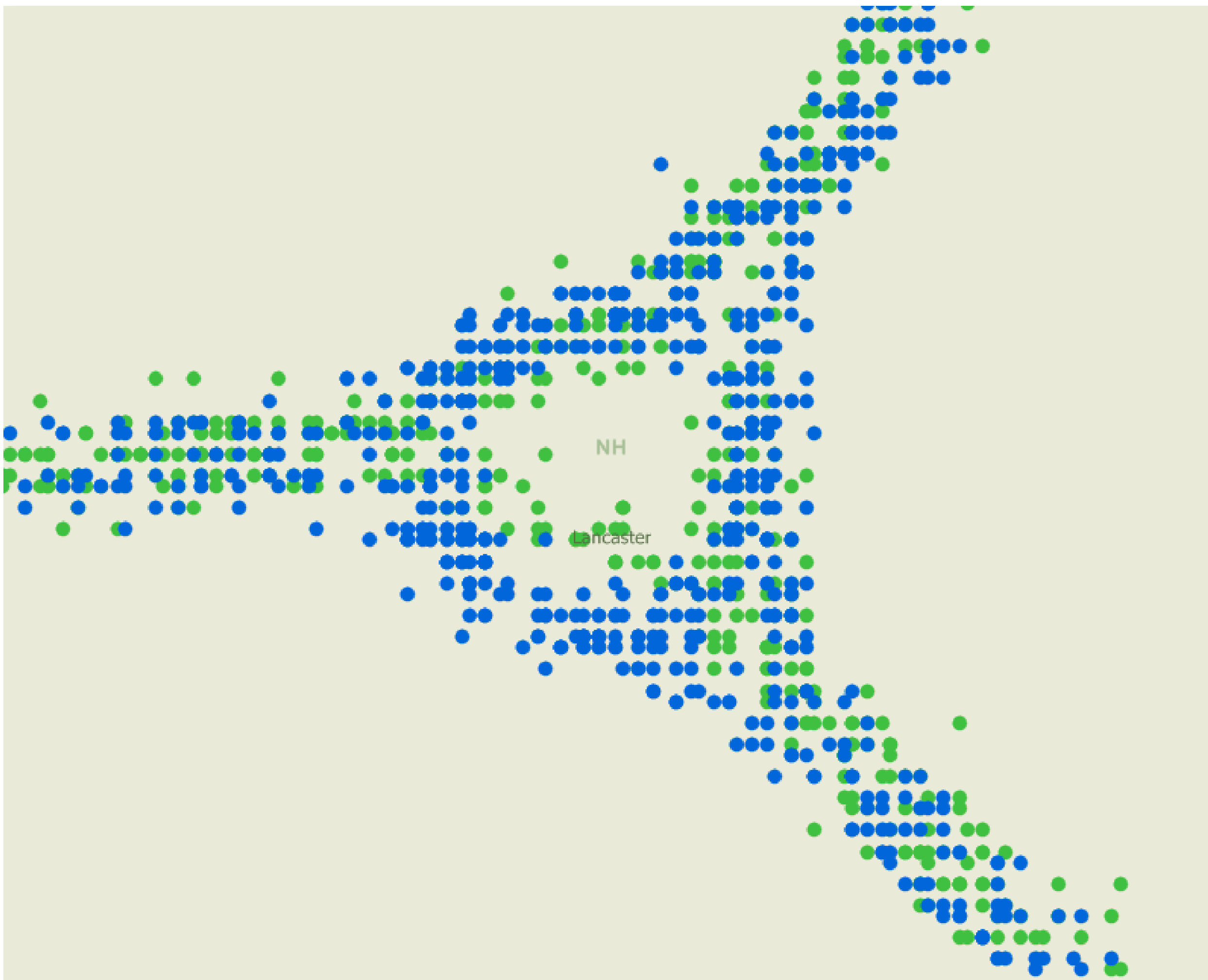


Figure 9 GPS Data Points Corresponding to the RSIC Service of the Lancaster Roundabout

GPS data were obtained for each dispatch event in January and February of 2016 and 2017, and for a few events in March 2017. After this time, the data logger had likely reached its maximum storage capacity, so the device did not continue recording points.

2.3 NOAA WEATHER DATA FOR STORM IDENTIFICATION

Daily weather data was obtained from the NOAA's GHCND (Global Historical Climatology Network-Daily) for classification of days by winter storm type. The GHCND is an integrated database of daily climate summaries from land surface stations across the globe, comprised of daily climate records subjected to a common suite of quality assurance reviews. The GHCND contains records from over 100,000 stations in 180 countries and territories, including maximum and minimum temperature, total daily precipitation, snowfall, and snow depth. For this project, GHCND data was obtained for every day of January, February, and March of 2016 and 2017 for the Lancaster, New Hampshire weather station.

2.4 COSTS AND RATES USED IN THE CALCULATION TOOL

The development of the Calculation Tool required the use of industry-accepted costs and average rates to allow the results of this study to be scaled-up to season-long monetary impacts. Table 1 provides a list of the unit costs and average rates that were gathered for use as default values in the Calculation Tool, including the source of each.

Table 1 Unit Costs and Average Rates Used for Default Values in the Calculation Tool

Description	Cost / Rate	Per	Source
Fuel (Assumes On-Network Re-Fueling)	$ 6.00	gallon	Estimate based on discussions with Vermont Agency of Transportation directors, supervisors, and drivers in 2015, 2016, and 2017
Salt (Purchase & Delivery)	$ 75.00	ton	Estimate based on a June 2017 email from Ken Valentine, Central Garage Supervisor, Vermont Agency of Transportation
Truck Operation (Driver + Vehicle)	$ 107.00	vehicle-hour	Estimate based on discussions with Vermont Agency of Transportation directors, supervisors, and drivers in 2015, 2016, and 2017
Sidewalk Plow Operation (Driver + Vehicle)	$ 160.00	vehicle-hour	Estimate based on data provided in "Sidewalk Finances", Onondaga County Sustainable Streets Project Reference Document, June 2014.
Sidewalk Plow Speed	5 miles	hour	
No. of Sidewalk Dispatch Events	15	year	
Sidewalk Plow Fuel Efficiency	1.0 miles	gallon	Estimated by the authors from a variety of resources and discussions
Sidewalk Salt Application Rate	0.2 tons	mile	Estimate from Hossain and Fu (2015)
No. of Snowplow Dispatch Events	50	year	

Description	Cost / Rate	Per	Source
No. of Passes	4.0	dispatch	Estimate based on discussions with Vermont Agency of Transportation directors, supervisors, and drivers in 2015, 2016, and 2017
Truck Fuel Efficiency	6.0 miles	gallon	http://www.fuelly.com/truck/international/7400
Tow-Plow	$ 150,000	each	Estimate based on a March 7, 2017 email from Robert Lannert, President, Snow King Technologies
Sidewalk Plow	$ 110,000	each	Estimate based on a December 2014 fixed-price quote from MacQueen Equipment to the State of Minnesota for a sidewalk tractor with plow, spreader, and blower
Plow Truck	$ 200,000	each	Estimate based on a June 2017 email from Ken Valentine, Central Garage Supervisor, Vermont Agency of Transportation

CHAPTER 3: METHODOLOGY

3.1 GPS DATA ANALYSIS

The GPS data points for 2016 and 2017 were compared using the date and time fields to assemble the points into trips, so that each point was assigned to a specific trip. These trips correspond to passes of the RSIC vehicle through the construction area. The elapsed time between points was used to assign them to trip segments. For the Lancaster Roundabout project, a 1-km buffer was created around the intersection to limit the set of points for analysis, and the average speed of the RSIC vehicle and the average time through the construction area were calculated for each trip segment, and trip segments were grouped by day for connection to storm events.

Daily weather from NOAA was used to classify storm intensities. The meteorological data were used to create a simple storm classification based on Nixon and Qiu (2005) so that each trip segment could be assigned to a specific type of storm. Each trip was assigned a storm classification based on the temperature and precipitation classes used by Nixon and Qiu (2005), shown in Table 2.

Table 2 Storm Classifications Used in this Project

Storm Class	Precipitation Class (Based on Snowfall Depth)	Temperature Class (Based on Daily Max. Temp.)
1	Light snow (< 2 in.)	Warm (> 32° F)
2	Light snow (< 2 in.)	Mid-Range (25 to 32° F)
3	Light snow (< 2 in.)	Cold (< 25° F)
4	Medium snow (2- 6 in.)	Warm (> 32° F)
5	Medium snow (2- 6 in.)	Mid-Range (25 to 32° F)

It should be noted that the daily maximum temperature was used in the derivation of the classification scheme and not the daily minimum or a calculated average temperature. In order to align these storm classes with the "low-salt" and "high-salt" storm intensities used in the Integrated RSIC Routing Model, classes 1 and 3 were aggregated as "low-salt" storms, and classes 2, 4, and 5 were aggregated as "high-salt" storms.

3.2 DEVELOPMENT AND APPLICATION OF THE INTEGRATED ROADWAY SNOW & ICE CONTROL ROUTING MODEL

The integration of the three tools was accomplished by adding computer code to the existing RSIC allocation and routing tool to run the other tools in a logical sequence. The existing computer code was also streamlined so that the entire process could be run in TransCAD, without the need for additional coding or model platforms.

3.2.1 Map Layer Development

The base node/link layer for this project was the snowplow routing network used in previous projects for Vermont, consisting of all roads and highways in the statewide travel model network. A variety of additional updates were made to this road network – new fields, new roadways, new turnarounds, and updates to the list of "stops" to be serviced. New turnarounds were added on I-89 in Burlington, on I-93 at Exit 1, at the intersection of State Route 279 and U.S. Route 7, and along U.S Route 4 at Exits 3, 4, 5 and 6. Two new attributes were added to the road layer, one to represent the Id field of the original, un-split link, and the other to represent the in-state length of a roadway that crosses the Vermont border. This step was necessary to avoid allocating vehicles to a garage based on roadway length that the state is not responsible for. In the routing model, roadways are represented as "stops" where salt is "delivered", at rate of either 200 lbs/mile (low-salt) or 500 lbs/mile (high-salt).

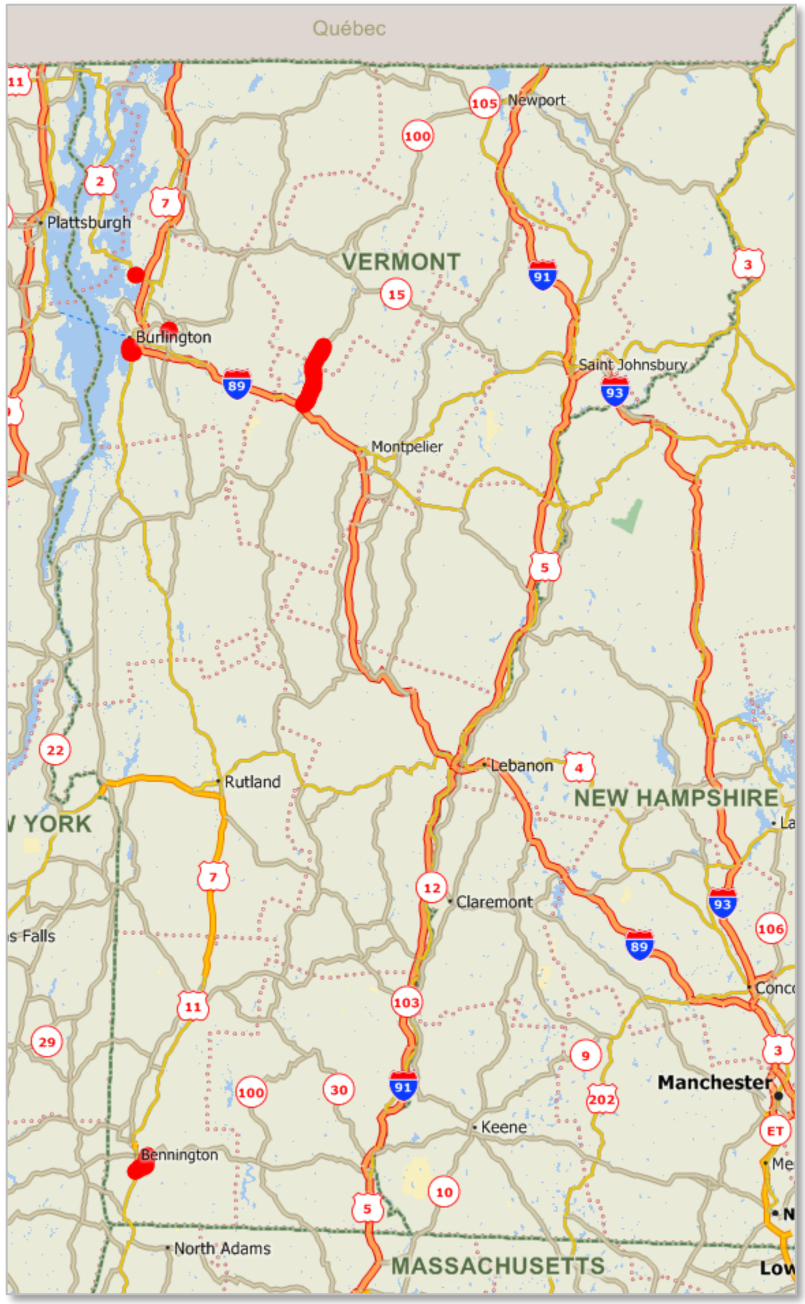


Figure 10 Final 5 case studies (in red) selected for analysis with the RSIC model

New roadways were added to the routing network to represent the case-study projects being evaluated with the model, at the locations shown in Figure 10. Each of these new roadways was then split using the “Dualize” function in TransCAD to represent the bi-directionality needed for accurate plow routing, and accurate turnaround points were incorporated for the new roadways. As an example of this process, the final road network representation for the Champlain Parkway project is shown in Figure 11.

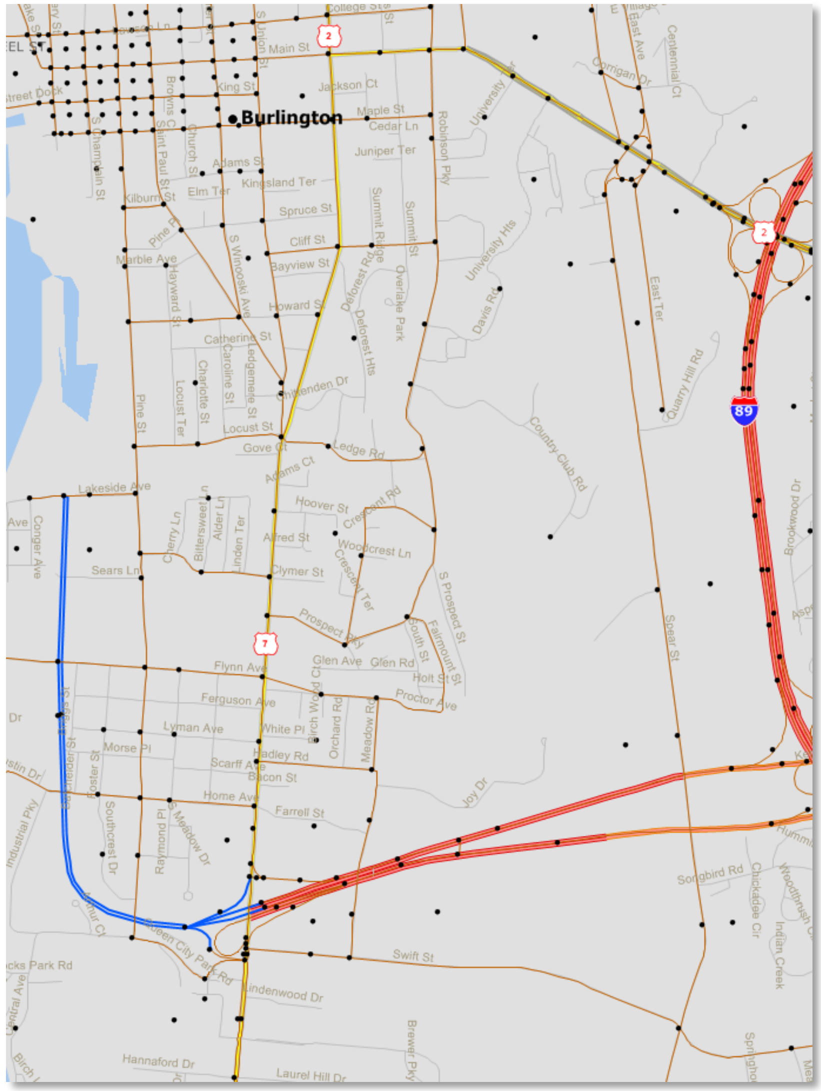


Figure 11 Roadways representing the Champlain Parkway project (in blue), as added to the routing network (brown)

Finally, new “stops” were added as midpoints of each new link in the routing network, using the TransCAD “Connect…” tool, which allows selected segments to be split at their midpoint. Once the new routing network was complete, several “cleanup” steps were taken to make the eventual route evaluation process more efficient. A new SpecialLinkType field was added to indicate a road segment that is a VTrans garage driveway, a truck turnaround on a divided highway, or a truck turnaround at the state border.

3.2.2 Integration of Models

A new scripted procedure was developed in TransCAD’s propriety programing language, to run the Integrated RSIC Model in TransCAD 7.0. The procedure consists of three primary processes – the network clustering and initial truck allocation, the route design, and the route evaluation & re-allocation. The procedure is initiated once the following parameters have been specified:

- Storm Intensity – low-salt (LS): 200 lbs/mile or high-salt (HS): 500 lbs/mile
- Road Network Scenario – normal (“full”) or omitting the project in question
- Allocation Method – by miles of roadway each depot is responsible for, or by roadway criticality each depot is responsible for

The procedure is initiated by calculating the total miles of roadway or the roadway criticality (as measured by the Network Robustness Index, or NRI) that each garage is responsible for servicing. Garages act as “Depots” for the routing procedure, providing a starting/ending point for all routes, as well as a source of salt resupply. The initial allocation begins using the official truck table for Vermont’s fleet, consisting of the detailed description of every truck used for RSIC in the state (Table 3).

Table 3 Vermont RSIC Truck Table

Type	Count	Make & Models	Average Model Year	Salt Capacity (tons)
1	10	International 4400, 4700, 4900, and 7300	2004	2.5
2	34	International 7400	2011	6
3	111	International 7400, 7500	2005	7.5
4	3	International 7600 6X4	2009	7.8
5	12	International 7500	2008	8.3
6	19	International 7600	2012	9.9
7	60	International 2574, 7600	2006	14.4

To determine the number of trucks allocated to each garage, the garage’s share of statewide roadway mileage or roadway criticality (NRI times length) is calculated and that fraction of the total RSIC fleet is allocated to the garage. For example, in a state with 5,000 miles of roadway, a garage responsible for 500 miles of roadway would be assigned 10% of its RSIC truck fleet (500/5,000). The only exception to this calculation is that each garage is guaranteed at least one truck. If a garage’s allocation percentage would yield less than 1 truck, its allocation is rounded up to 1.

Once each garage’s share of the statewide RSIC fleet is determined, specific trucks are assigned from the official truck table, beginning with the highest capacity trucks (Type 7) in the fleet and proceeding to the lowest capacity. In this way, garages with only one truck are ensured a Type 7 truck, and garages with many trucks get a variety of truck sizes.

Using the initial truck allocation, a set of optimized routes is developed using the length of each roadway to represent a demand for salt at a rate of either 200 lbs per mile (low-salt storm) or 500 lbs/mile (high-salt storm). The only exception that is made to the normal route optimization algorithm is that every effort is made to route all of the vehicles that have been assigned to each garage, the goal being to not leave any vehicles in the RSIC fleet idle. This constraint is satisfied by carefully increasing the “time windows”, within which a vehicle must complete its route, in an iterative algorithm that stops immediately after all of the links have been ensured service. Continued growth of the time windows, or the setting of artificially large time windows, would cause the algorithm to minimize the number of trucks used by each garage, leaving much of the statewide fleet idle. When the iterations are complete and all links in the state are ensured service, the routing stops and route designs are saved to a master file, including turn-by-turn directions and vehicle types for every route. In spite of this special step, some garages still do not route all of their trucks, indicating that the initial allocation provided too many trucks to efficiently service that garage's share of the state's roadways.

Once the optimized routes have been designed, they are evaluated and a set of summary statistics for each route is saved to an output table. These summary statistics include:

- Home Garage ("Depot")
- Vehicle Type
- Total Salt Needed (pounds)
- Route distance (miles)
- Number of "Stops" (Segments Serviced)
- Service time (minutes)

From these route summary tables, a depot summary table is created, with the following summary statistics for each home garage, or "depot":

- Initial vehicle allocation
- Number of routes serviced
- Number of unused vehicles
- Total RSIC effort (vehicle-minutes of travel)
- Longest route (miles)
- Service time (minutes)
- Average route time (minutes)
- Total salt used (pounds)
- RSIC stress (minutes)
- Salt ratio

If any unused vehicles are present at any of the garages statewide, then a re-allocation is implemented.

For the re-allocation, first the specific vehicle that has been left idle and the garage where it is located are identified. Next, that vehicle is re-assigned to a new garage based on one of two factors under the current routing/storm-intensity scenario. The garage that is having the most difficulty servicing its network cluster gets priority for vehicle re-allocation. For the low-salt storm scenario, idle vehicle(s) are re-assigned based on the "RSIC stress", which is simply the sum of the average route length and the service time. For the high-salt storm scenario, the RSIC stress is represented by the "salt ratio" (SR), or the ratio of salt needed to service the garage's network cluster and the salt capacity of the vehicles currently allocated to it. For both storm-intensity scenarios, idle vehicles are re-allocated according to their available salt capacity. That is, the idle vehicles with the higher salt capacity are allocated to the garages exhibiting the highest RSIC stress.

In this way, garages with highest RSIC stress are assumed to be the ones most in need of an additional vehicle. Once these vehicles are re-assigned, a new allocation table is created and a new set of optimized routes are designed. This process is repeated until a set of optimized routes is created that results in all of the vehicles in the RSIC fleet being used.

In order to evaluate the effects of new capital projects on RSIC burden, links representing the new projects were added to the RSIC road network, as if they had been constructed. Next, new criticalities were calculated for each roadway in this “Full” network using the forecasted travel demand for the year when the project is expected to be completed. The Integrated RSIC Model was then run using the new criticality values and the new roadway miles in the “Full” network and a set of optimized routes were designed. Finally, the links representing each individual project were removed one at a time, and the Integrated RSIC Model was repeated for the roadway network without the capital project in question. The optimized sets of routes designed with and without the project in question represent its effect on RSIC burden. From those two sets of routes, the following outputs representing the total RSIC burden, were compared:

1. Total RSIC effort
2. Final vehicle allocation
3. Service-time

This process is illustrated in the Integrated RSIC Model flowchart provided in Figure 12.

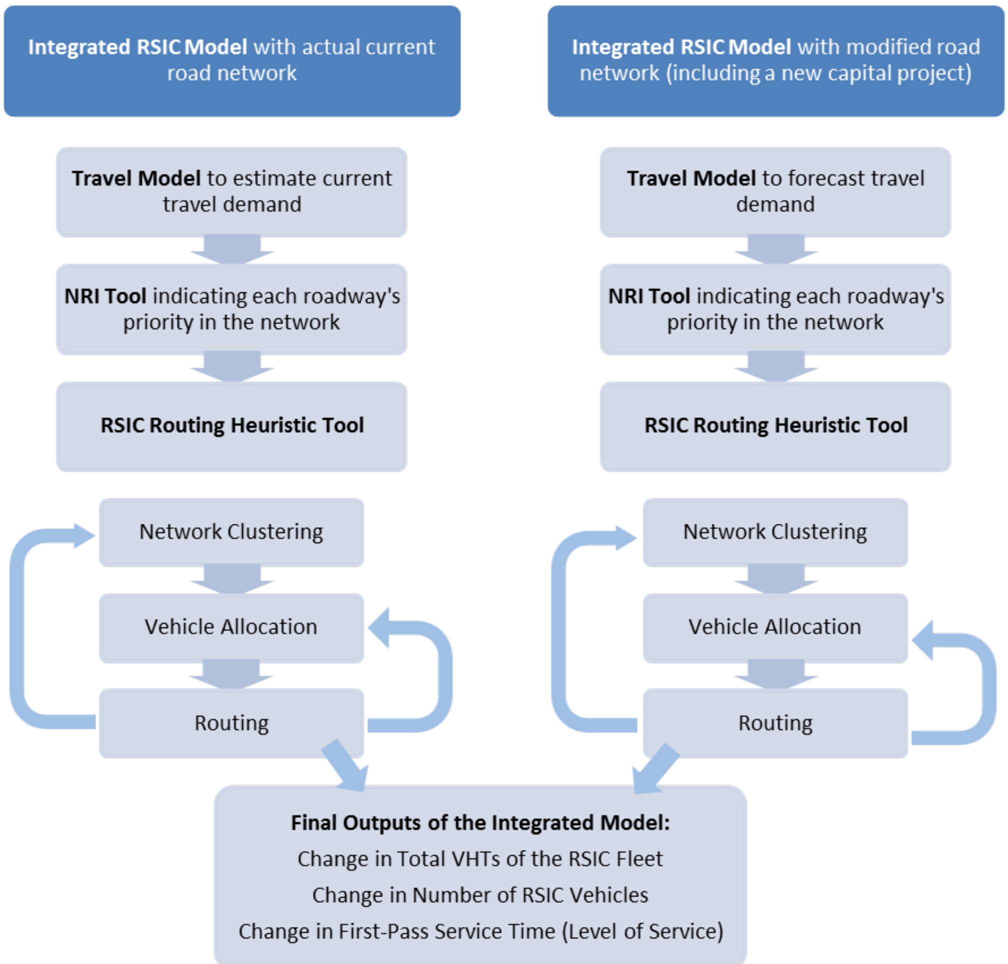


Figure 12 Integrated RSIC Model capital project evaluation flowchart

3.2.3 Integrated RSIC Model Case Study Application

For each application of the Integrated RSIC Model, outputs were available for the specific garage that is responsible for the project in question, but also for the entire state system. Since "ripple effects" from the re-allocation of trucks resulting from the project are possible, the change in total RSIC effort was calculated for the entire state system. However, the changes in final vehicle allocation and service time were calculated for the specific garage where the project is located. Separate applications of the model were necessary to evaluate (1) vehicle allocation changes and (2) total effort and service time changes, so that total effort and service time could be calculated for an equivalent number of trucks.

Table 4 provides a summary of the application scenarios of the Integrated RSIC Model that were necessary for this project.

Table 4 Integrated RSIC Model application scenarios

Allocation Method / Storm-Intensity Combination		Project Being Evaluated					
		Full (Baseline) Network	Champlain Parkway, ChPa	Crescent Connector, CrCo	US Route 2 Left-Turn Lanes, Rt2Lefts	State Route 100 Lane Addition, Rt100Lane Adds	Bennington ByPass, Southern Segment, BennBP
Miles	Low-Salt Storm	X	X	X	X	X	X
Miles	High-Salt Storm	X	X	X	X	X	X
NRI	Low-Salt Storm	X	X	X	X	X	X
NRI	High-Salt Storm	X	X	X	X	X	X

Any scenario which results in a different vehicle allocation between the Full (Baseline) Network and the project being evaluated will also require a second application of the Integrated RSIC Model with the vehicle allocations matched in order to make a valid comparison of RSIC effort. Therefore, between 24 and 48 applications of the Integrated RSIC Model were conducted. Each run of the Model requires 2-3 hours of processing time, for a project total of between 48 and 144 hours of runtime.

3.3 CALCULATION TOOL DEVELOPMENT

The outputs of the Integrated RSIC Model applications were used to populate a calculation tool for practitioners to make estimates of the RSIC burden increase from a variety of common project types. From the outputs of the Integrated RSIC Model runs, the team developed an Excel-based decision-support tool to allow users to enter their own specific monetary costs for fuel, salt, labor, and vehicle operation and get an estimated cost for the impact of each type of capital improvement investigated. The tool is intended to be used by operations planners and supervisors to justify budget requests in advance of a new capital project.

MS Excel provides a user-friendly computational platform for automating calculations summarizing the impact of capital improvements on RSIC burden. Spreadsheet-based decision-support tools built in Excel allow users to examine scenarios, change inputs, and view numeric and visual summaries in real-time.

This tool will be useful in estimating how new capital projects will create a need for additional RSIC budgetary resources. The tool was created as an extension of Excel using Visual Basic for Applications (VBA), the programming language for Excel. With VBA, a user-friendly interface can be built in the familiar spreadsheet environment. When the user is not likely to be interested in the mathematical form of the underlying model parameters, only in its application to a specific decision task, this type of extension is perfectly suited. The familiar spreadsheet interface gives users total access to the model's functionality via simple inputs and provides results as nontechnical outputs. The outputs of the Integrated RSIC Model application in Vermont were converted into unit rates for measuring RSIC burden increase, in units of (1) vehicle-minutes of effort, (2) new RSIC vehicles, and (3) loss of service time. These rates make the Excel tool generalizable to all of the Clear Roads' member states.

CHAPTER 4: RESULTS

4.1 INCREASED RSIC BURDEN FOR THE ROUNDABOUT IN LANCASTER, NEW HAMPSHIRE

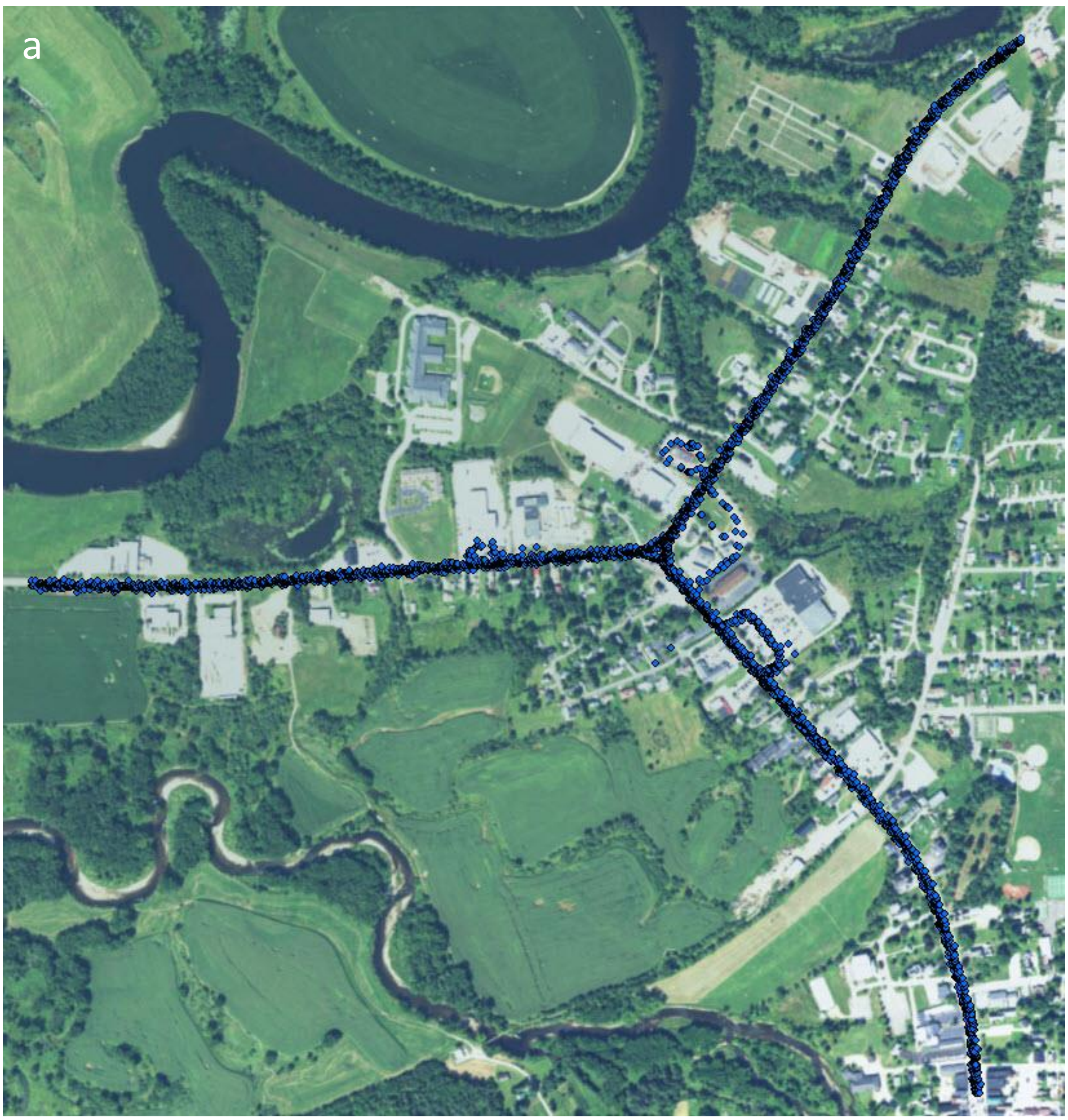
The original GPS datasets for 2016 and 2017 contained 79,329 and 70,776 data points, respectively. A total of 18 trips were identified for each year. The dates and total durations of each of these trips are shown in Table 5, along with the storm classification defined by the precipitation and temperature data.

Table 5 Dates, durations and storm classification data for each RSIC trip in the GPS dataset

Date(s)	Duration (hrs)	Precip. (in.)	Max. Temp. (°F)	Min. Temp. (°F)	Storm Classification
11-Jan-16	8.3	0.01	30	4	2
13-Jan-16	6.2	0.01	19	-2	3
15-Jan-16	3.8	0.6	23	-1	3
16-Jan-16	6.5	2.6	32	20	5
17-Jan-16	1.5	1.4	27	13	2
18-Jan-16	13.3	1.7	21	3	3
21-Jan-16	1.0	0	17	-3	3
29-Jan-16	0.4	0.9	33	19	1
3-Feb-16	1.4	0	42	27	1
5-Feb-16	1.0	0.01	32	12	2
13-Feb-16	2.2	0	12	-18	3
16-Feb-16	15.3	0	54	25	1
17-Feb-16 & 18-Feb-16	29.5	0	31	15	2
20-Feb-16	2.7	2	40	30	4
21-Feb-16	9.2	0	38	15	1
22-Feb-16 & 23-Feb-16	12.9	0	26	1	2
24-Feb-16	8.5	0.6	50	26	1
25-Feb-16	10.2	1.4	60	20	1
12-Jan-17	10.6	0.01	49	33	1
13-Jan-17	4.1	0.01	33	0	1
15-Jan-17	1.6	0.4	28	3	2
18-Jan-17	6.2	1.1	30	25	2
19-Jan-17	14.2	0	35	27	1
20-Jan-17	23.9	0	34	25	1
21-Jan-17	11.9	0	38	29	1
24-Jan-17	6.9	1.2	38	27	1
25-Jan-17	1.8	0.01	31	28	2
27-Jan-17	1.6	1.3	33	25	1
4-Feb-17	7.1	0.01	23	4	3
6-Feb-17	8.5	1.3	20	12	3

Date(s)	Duration (hrs)	Precip. (in.)	Max. Temp. (°F)	Min. Temp. (°F)	Storm Classification
7-Feb-17 & 8-Feb-17	28.0	2.7	29	13	5
9-Feb-17	4.9	1.8	17	-6	3
14-Feb-17	1.7	0.7	28	6	2
15-Feb-17	9.8	2.8	26	19	5
16-Feb-17	1.6	0.01	27	-2	2
7-Mar-17	8.0	0	55	38	1

Given the routing differences between years for these trips, a buffer was used to extract only data points within a 1-km radius of the intersection being converted to a roundabout between 2016 and 2017. Figure 13a and 13b show the data points within the 1 km buffer of the intersection for 2015-2016 and 2016-2017, respectively.



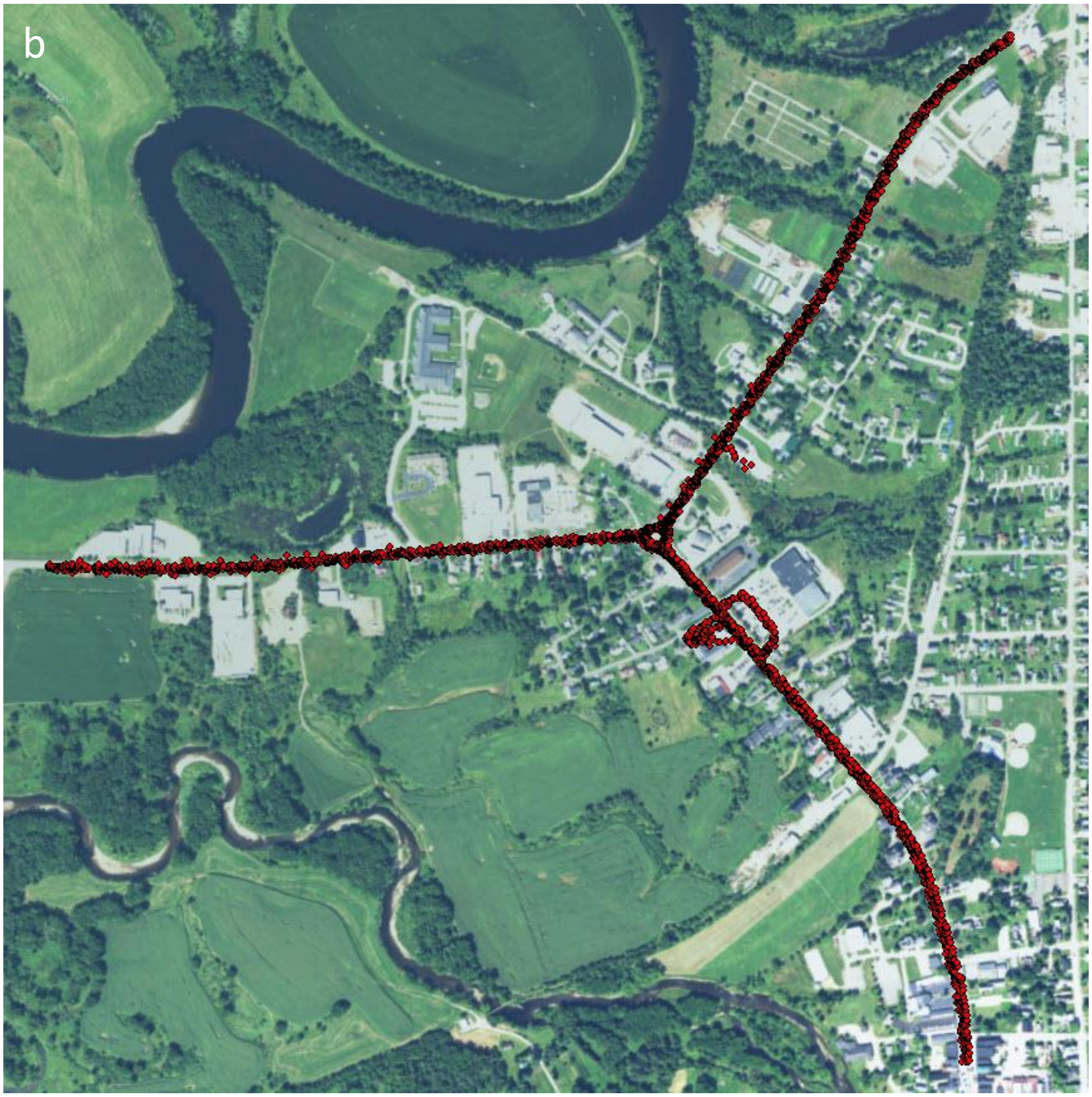


Figure 13 GPS data points within the 1 km buffer of the intersection for 2015-2016 (a) and 2016-2017 (b)

98 trip segments were created for 2016 and 108 trip segments were created for 2017, indicating that the average number of passes for each season were 5.5 and 6.0, respectively. Table 6 summarizes and compares the average time taken to make a RSIC service pass and the average speed of the service, as calculated from trip segments grouped by specific winter storm category.

Table 6 Average time and average speed of RSIC service by storm class

Year	# of Trip Segments	Storm Class	Avg. Time (min.)	Avg. Speed (kph)
2016	27	1	3.82	36.2
2016	17	2	3.26	37.8
2016	36	3	4.23	31.9
2016	6	4	3.02	36.8
2016	12	5	4.14	32.0

Year	# of Trip Segments	Storm Class	Avg. Time (min.)	Avg. Speed (kph)
2017	37	1	3.72	35.9
2017	21	2	5.03	31.2
2017	25	3	3.34	36.8
2017	0	4	-	-
2017	25	5	4.28	32.2

The same set of outputs for the aggregated classes, representing a storm that would not be likely to require a high amount of salt (classes 1 and 3 – low-salt) and a storm that would (classes 2, 4, and 5 – high-salt), are shown in Table 7, although now the aggregate average time to service the project area is also provided, - representing the average time multiplied by the average number of passes.

Table 7 Average time and average speed of RSIC service by storm severity

Year	# of Trip Segments	Storm Severity	Avg. Speed (kph)	Avg. Time (min.)	Average Number of Passes	Aggregate Avg. Time (min.)
2016	63	LS	33.7	4.06	5.5	22.3
2016	35	HS	35.6	3.52	5.5	19.4
2017	62	LS	36.2	3.56	6.0	21.4
2017	46	HS	31.7	4.62	6.0	27.7

As seen in the table, the introduction of the roundabout had mixed effects on RSIC burden. It resulted in a decrease in average speed and an increase in the number of passes needed for the high-salt snow events. This finding is consistent with what was expected by field reports from drivers and supervisors. However, the effect was reversed for low-salt storms, where the roundabout increased the RSIC speed slightly. The result was an increase in RSIC effort of 8.3 minutes for the high-salt storm, and a decrease of 0.9 minutes for the low-salt storm.

The reason for this finding could be related to the fact that cars are also present in the roundabout, and will have an effect on the speed and effectiveness of the RSIC service. The absence of cars in the roundabout will allow the RSIC vehicle to proceed through more quickly, but congestion or stopped vehicles in the roundabout will cause the service to take longer. Overall, though, the findings were consistent with expectations, with a net slowing effect of the roundabout on RSIC service.

4.2 INCREASED RSIC BURDEN FOR THE CHAMPLAIN PARKWAY IN BURLINGTON, VERMONT

The RSIC burden created by the proposed construction of the Champlain Parkway in Burlington (Figure 11) was measured as the difference in the final allocation to the garage responsible for this roadway (the Colchester garage), then also as the increase in service time created by the project in the Colchester garage or elsewhere in the state, and finally also as the increase in total effort, as measured by statewide vehicle-minutes of travel per pass. The results of the Integrated RSIC Model applications conducted for this project are provided in Table 8.

Table 8 Results of Integrated RSIC Model applications for the Champlain Parkway project

Allocation Method	Scenario	Storm Severity	Final Allocation	District Service Time (min.)	Statewide Service Time (min.)	Total Effort (vehicle-minutes)
Miles	Without	Low Salt	9	123	133	15,289
	With		9	132	133	15,471
	With		11	NA		
	Without	High Salt	9	130	133	15,402
	With		9	130	133	15,813
	With		10	NA		
NRI	Without	Low Salt	16	113	133	15,613
	With		17	NA		
	Without	High Salt	16	103	128	15,601
	With		17	NA		

As shown in the table, the application of the Integrated RSIC Model with the project in place resulted in an increased vehicle allocation for its garage in all four allocation method / storm severity combinations. For the low-salt storm scenarios, the average allocation increase was 1.5 trucks (11–9 & 17–16), whereas the increases for the high-salt storm scenarios were both 1.0 trucks (10–9 & 17–16). To calculate the increased total effort from the project, the scenarios with identical vehicle allocations were compared. For the low-salt scenario, the project resulted in an additional 182 (15,471 – 15,289) vehicle-minutes of travel per pass. For the high-salt scenario, the project resulted in an additional 411 vehicle-minutes of travel per pass. To find the increased service time from the project, the largest of the increases for the entire state and for the specific garage where the project is located was calculated. For the low-salt scenarios, the highest service-time increase was 9 minutes (132 – 123). For the high-salt scenarios, the highest service-time increase was 0 minutes.

4.3 INCREASED RSIC BURDEN FOR THE CRESCENT CONNECTOR IN ESSEX JUNCTION, VERMONT

The RSIC burden created by the proposed construction of the Crescent Connector in Essex Junction (Figure 14) was measured as the difference in the final allocation to the garage responsible for this roadway (the Colchester garage), then also as the increase in service time created by the project in the Colchester garage or elsewhere in the state, and finally also as the increase in RSIC effort, as measured by statewide vehicle-minutes of travel per pass. The results of the nine integrated model applications conducted for this project are provided in Table 9.

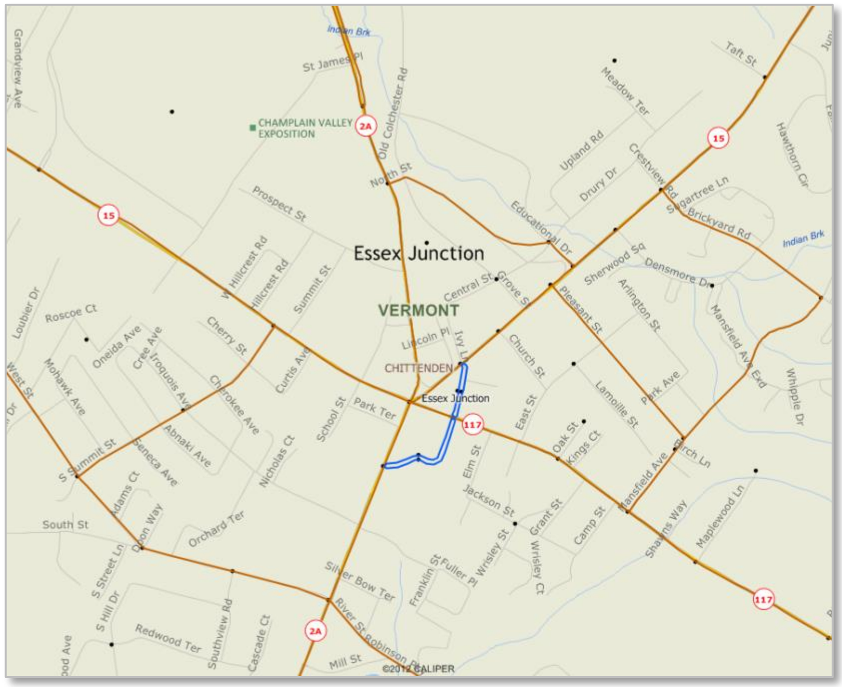


Figure 14 Roadways representing the Crescent Connector project (in blue), as added to the routing network (brown)

Table 9 Results of Integrated RSIC Model applications for the Crescent Connector project

Allocation Method	Scenario	Storm Severity	Final Allocation	District Service Time (min.)	Statewide Service Time (min.)	Total Effort (vehicle-minutes)
Miles	Without	Low Salt	9	124	133	15,287
	With		9	132	133	15,471
	With		11	NA		
	Without	High Salt	10	124	133	15,497
	With		10	125	138	15,522
NRI	Without	Low Salt	17	105	133	15,522
	With		17	105	137	15,673
	Without	High Salt	17	114	131	15,831
	With		17	105	166	16,056

As shown in the table, the application of the integrated RSIC model with the project in place resulted in an increased vehicle allocation for its garage in one of the four allocation method / storm severity combinations. For the low-salt storm scenarios, the average allocation increase was 1 truck (11 – 9 & 17 – 17), whereas the increases for the high-salt storm scenarios were both 0 (10 – 10 & 17 – 17). To calculate the increased total effort from the project, the scenarios with identical vehicle allocations were compared. For the low-salt scenarios, the project resulted in an additional average of 168 (15,471 – 15,287 & 15,673 – 15,522) vehicle-minutes of travel per pass, whereas the corresponding increase for the high-salt storm scenario averaged 125 vehicle-minutes of travel per pass. For the low-salt scenarios, the highest service-time increase was 8 minutes (132 – 124). For the high-salt scenarios, the highest service-time increase was 35 minutes (166 – 131).

4.4 INCREASED RSIC BURDEN FROM THE ADDITION OF LEFT-TURN LANES ON U.S. ROUTE 2 IN COLCHESTER, VERMONT

The RSIC burden created by the proposed addition of left-turn lanes for two of the four approaches at the intersections of US Route 2 and Clay Point Road in Colchester (Figure 15) was measured as the difference in the final allocation to the garage responsible for this roadway (the Chimney Corner garage), then also as the increase in service time created by the project in the Chimney Corner garage or elsewhere in the state, and finally also as the increase in total effort, as measured by statewide vehicle-minutes of travel per pass.

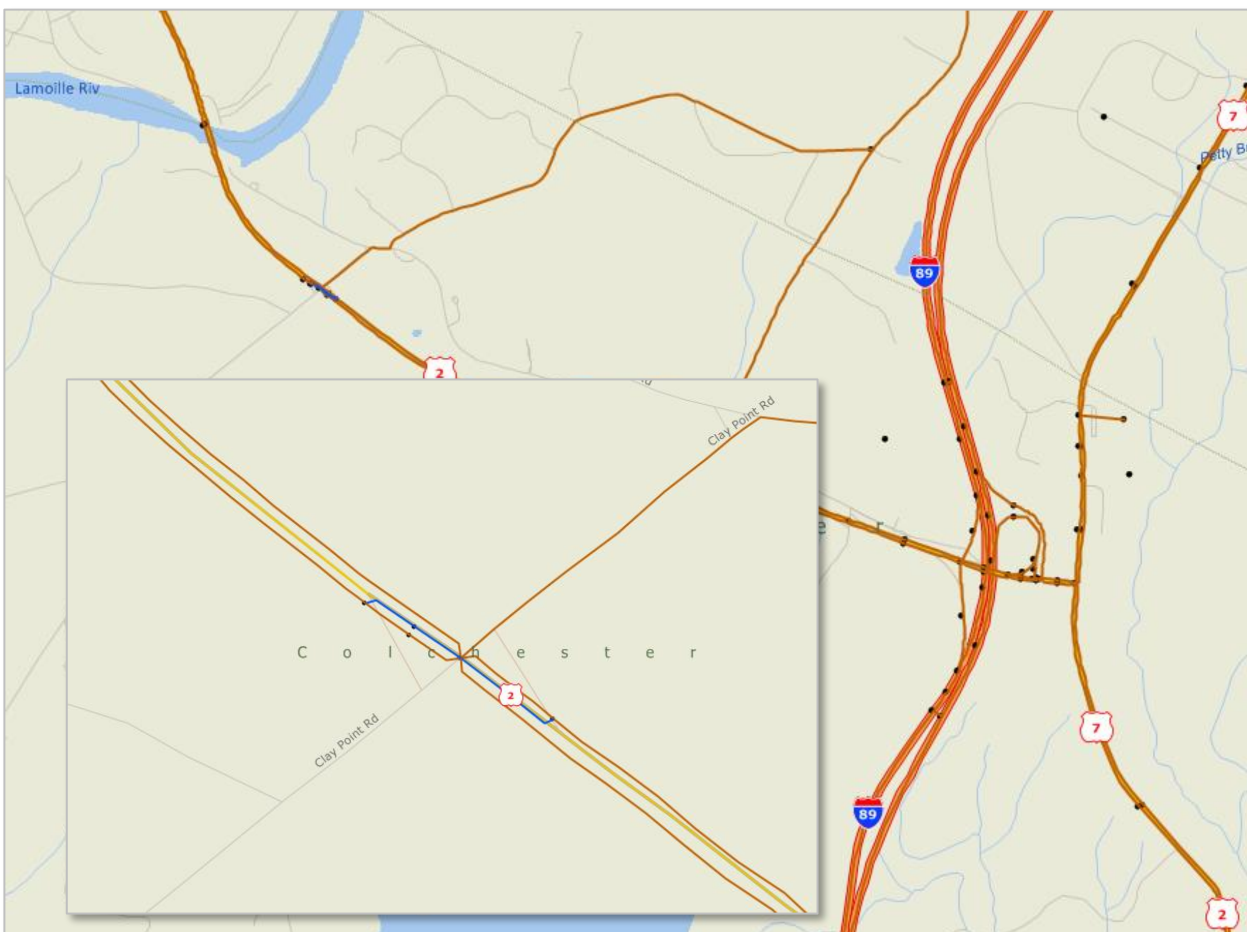


Figure 15 Roadways representing the Left-Turn Lanes on U.S. Route 2 project (blue in the inset), as added to the routing network (brown)

The results of the eight integrated model applications conducted for this project are provided in Table 10.

Table 10 Results of Integrated RSIC Model applications for the U.S Route 2 Left-Turn Lanes project

Allocation Method	Scenario	Storm Severity	Final Allocation	District Service Time (min.)	Statewide Service Time (min.)	Total Effort (vehicle-minutes)
Miles	Without	Low Salt	3	68	133	15,234
	With		3	82	133	15,479
	Without	High Salt	3	85	138	15,522
	With		3	83	133	15,770
NRI	Without	Low Salt	4	91	137	15,673
	With		5	NA		
	Without	High Salt	4	91	166	16,056
	With		5	NA		

As shown in the table, the application of the integrated RSIC model with the project in place resulted in an increased vehicle allocation for its garage in two of the four allocation method/storm severity combinations. For the low-salt storm scenarios, the average allocation increase was 0.5 trucks, whereas the increases for the high-salt storm scenarios were both 0.5 trucks. To calculate the increased total effort from the project, the two scenarios with identical vehicle allocations were compared. For the low-salt scenarios, the project resulted in an additional 245 vehicle-minutes of travel per pass, whereas the corresponding increase for the high-salt storm scenario was 248 vehicle-minutes of travel per pass. To find the increased service time from the project, the largest of the increases for the entire state and for the specific garage where the project is located was calculated. For the low-salt scenarios, the highest service-time increase was 14 minutes. For the high-salt scenarios, the highest service-time increase was 0 minutes.

4.5 INCREASED RSIC BURDEN FROM THE ADDITION OF A LANE IN EACH DIRECTION OF STATE ROUTE 100 IN WATERBURY, VERMONT

The RSIC burden created by the envisioned addition of one lane of travel in each direction of State Route 100 in Waterbury (Figure 16) was measured as the difference in the final allocation to the garage responsible for this roadway (the Middlesex garage), then also as the increase in service time created by the project, and finally also as the increase in total effort, as measured by statewide vehicle-minutes of travel per pass.

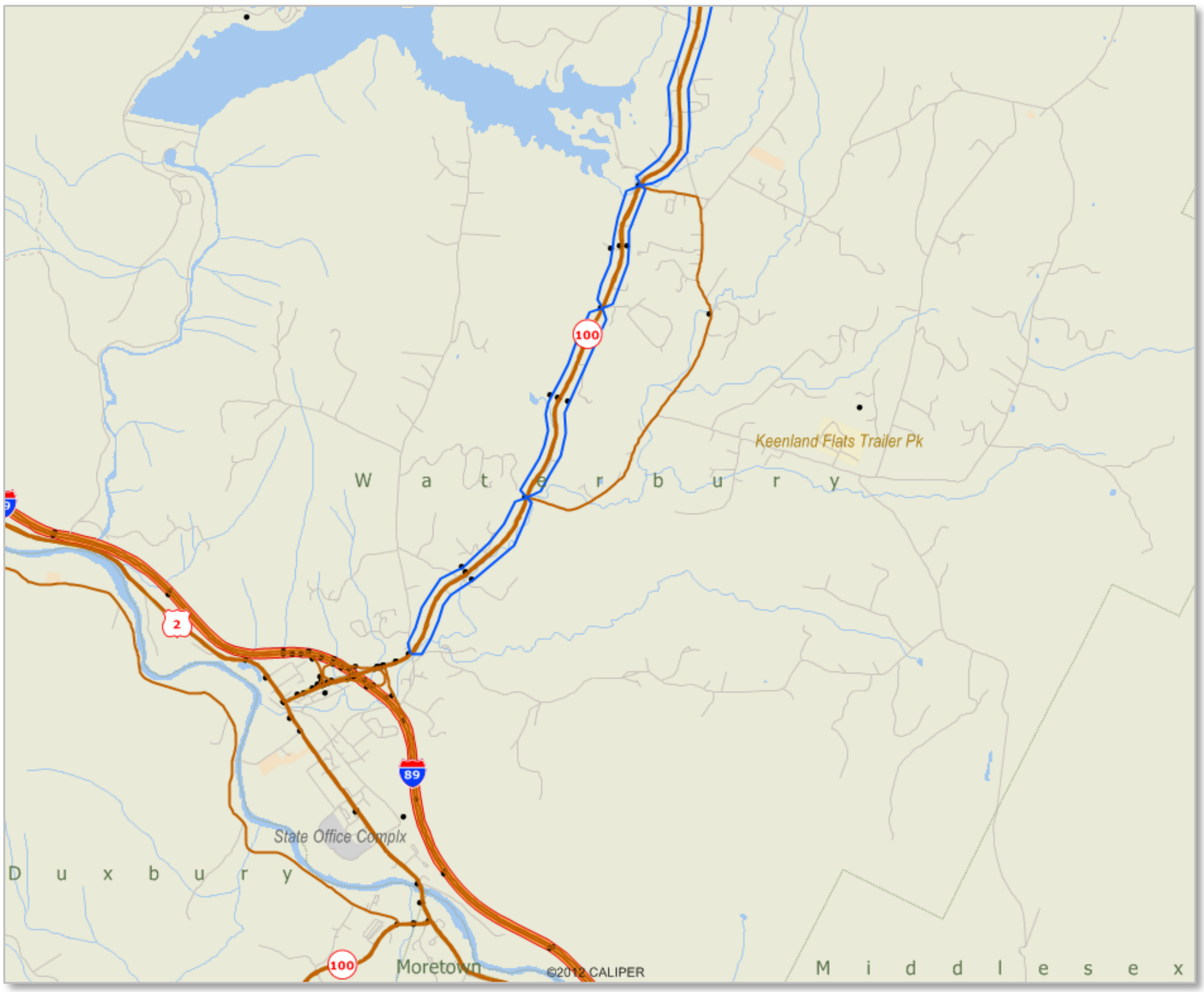


Figure 16 Roadways representing the Addition of a Lane in Each Direction on U.S. Route 100 project (in blue), as added to the routing network (brown)

The results of the 12 integrated model applications conducted for this project are provided in **Error! Not a valid bookmark self-reference.**.

Table 11 Results of Integrated RSIC Model applications for the State Route 100 Lane Addition project

Allocation Method	Scenario	Storm Severity	Final Allocation	District Service Time (min.)	Statewide Service Time (min.)	Total Effort (vehicle-minutes)
Miles	Without	Low Salt	7	101	133	15,234
	With		7	106	128	15,590
	With		8	NA		
	Without	High Salt	6	114	138	15,522
	With		6	130	130	15,467
	With		8	NA		
NRI	Without	Low Salt	8	94	121	15,165
	With		8	105	121	15,173
	With		9	NA		
	Without	High Salt	8	96	166	16,056
	With		9	NA		

As shown in the table, the application of the integrated RSIC model with the project in place resulted in an increased vehicle allocation for its garage in all four allocation method / storm severity combinations. For the low-salt storm scenarios, the average allocation increase was 1.5 trucks whereas the increases for the high-salt storm scenarios were both 1.0 trucks.

To calculate the increased total effort from the project, the scenarios with identical vehicle allocations were compared. For the low-salt scenarios, the project resulted in an additional average of 182 vehicle-minutes of travel per pass. For the high-salt scenario, the project resulted in a decrease of 55 vehicle-minutes of travel per pass statewide. This seemingly contradictory result occurs when the re-allocation process, which is critical for the high-salt scenario, results in a more efficient final allocation when the project is added, so other parts of the state benefit, offsetting the increased effort in the Middlesex district.

To find the increased service time from the project, the largest of the increases for the entire state and for the specific garage where the project is located was calculated. For the low-salt scenarios, the highest service-time increase was 16 minutes. For the high-salt scenarios, the highest service-time increase was 11 minutes.

4.6 SPECIAL CASE STUDY FOR A RURAL BY-PASS IN BENNINGTON, VERMONT

The RSIC burden created by the proposed construction of the Southern Segment of the Bennington Bypass in Bennington (Figure 17) was measured as the difference in the final allocation to the garage responsible for this roadway (the Bennington garage), then also as the increase in service time created by the project, and finally also as the increase in total effort. The results of the integrated RSIC model applications conducted for this project are provided in Table 12.

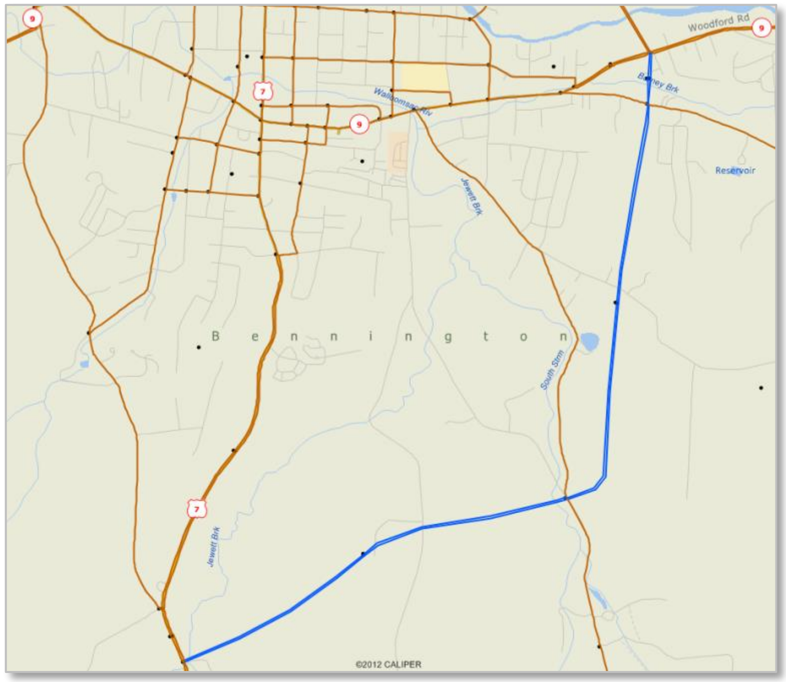


Figure 17 Roadways representing the Southern Segment of the Bennington Bypass project (in blue), as added to the routing network (brown)

Table 12 Results of Integrated RSIC Model applications for the Bennington Bypass project

Allocation Method	Scenario	Storm Severity	Final Allocation	District Service Time (min.)	Statewide Service Time (min.)	Total Effort (vehicle-minutes)
Miles	Without	Low Salt	7	90	133	15,594
	With		7	102	133	15,546
	With		6	NA		
	Without	High Salt	7	NA		
	Without		6	112	138	15,697
	With		6	98	138	15,522
NRI	Without	Low Salt	NA			
	With		7	105	137	15,673
	Without	High Salt	NA			
	With		7	106	166	16,056

As shown in the table, the application of the integrated RSIC model with the project in place resulted in a *decreased* vehicle allocation for its garage in all allocation method / storm severity combinations. The project also resulted in *decreases* in vehicle-minutes of travel per pass – 48 for the low-salt scenario and

175 for the high-salt scenario. For the low-salt scenario, the highest service-time increase was 12 minutes. For the high-salt scenario, the highest service-time increase was 0 minutes.

The rural bypass is a special case study that makes it unique among the other case studies because the RSIC burden actually *diminished* when a new road was added to the network, which is why the applications using the NRI allocation method were not completed. This decrease is created because the new roadway creates a shortcut from the edge of a route to the edge of another route that previously required "deadheading", or traversing links without providing RSIC service. Deadheading occurs when a roadway is traversed without providing service, either because it has already been provided by another route or because the roadway is not part of the state-maintained network.

So the new bypass create a shortcut for snow and ice control vehicles to bypass roads that are not part of the state-maintained network (in green in Figure 18) in the same way that it creates a shortcut for vehicles bypassing the downtown.

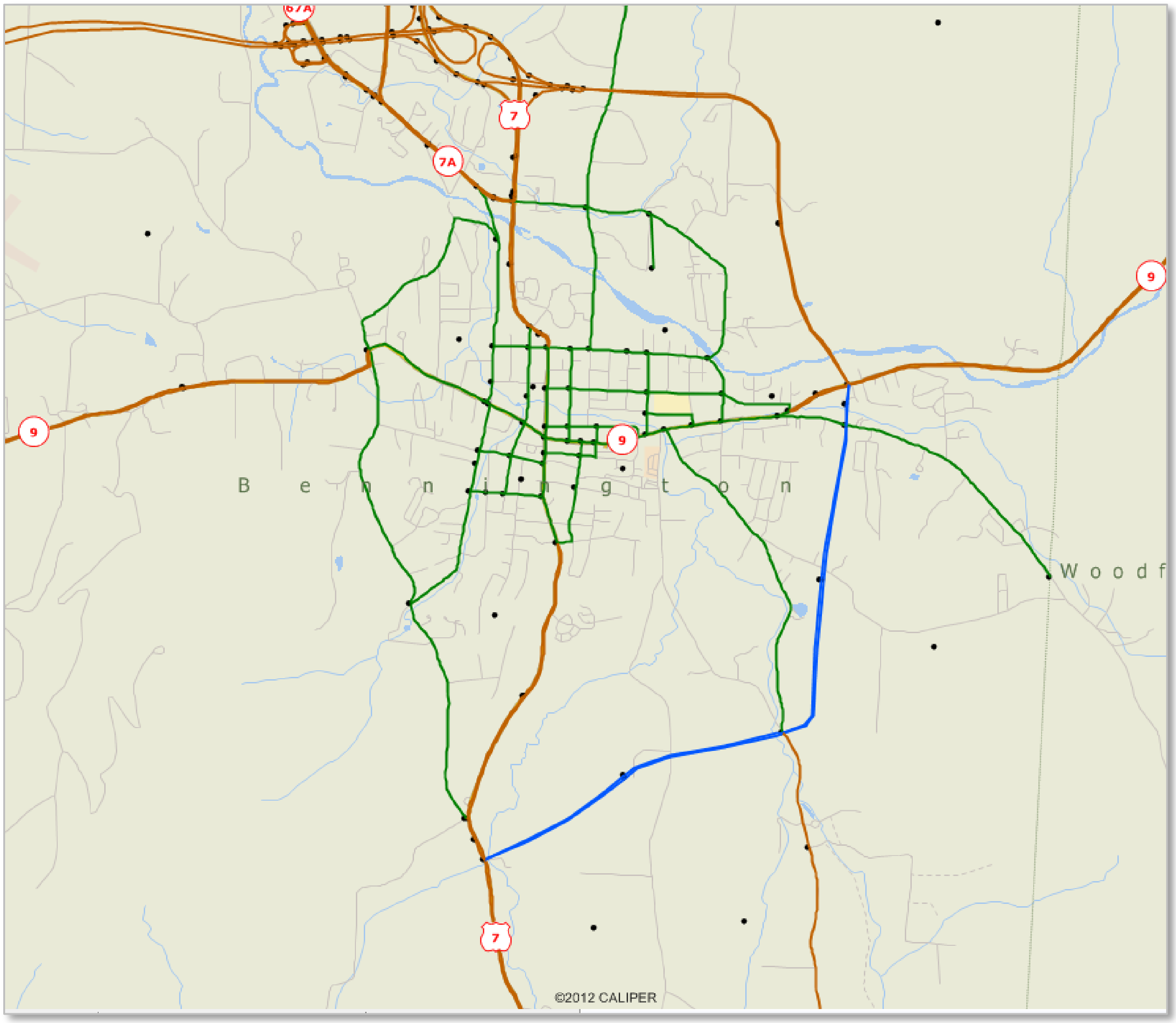


Figure 18 Roads that are not part of the state-maintained network (in green) are bypassed by the new project (in blue)

In this unique situation, additional resources are not required by the district where the rural bypass had been constructed, even though the roadway mileage it is responsible for has increased. However, this conclusion is only applicable to the specific network structure created by a rural state-maintained bypass around a small micropolitan "crossroads" community whose downtown roads are not the responsibility of the state agency. RSIC vehicles approach the small micropolitan community, stop servicing the roadway at a certain point and then drive through the downtown without providing service, then out of the small micropolitan community to the continuation of the RSIC route where the state-maintained roadway begins again. The new bypass creates a shortcut that makes the deadheading in the downtown community unnecessary and reduces the distance traveled.

4.7 SUMMARY OF RESULTS FOR USE IN THE CALCULATION TOOL

Table 13 contains a summary of the results of the Integrated RSIC Model applications for the increase in effort measured as increase in the total vehicle-minutes of travel for each pass.

Table 13 Summary of results of the Integrated RSIC Model applications for increased RSIC effort

Project ID	Project Type	Quantity	Unit	Region Type	Low-Salt Storm	High-Salt Storm	Average Unit Increase (min.)	
CrCo	New roadway, 1-lane either direction	0.55	miles	suburban	168	125	**266**	**per mi.**
ChPa	New roadway, 1-lane either direction	3.56	miles	urban	182	411	**83**	**per mi.**
Rt2Lefts	New left-turn lanes, 2 of 4 approaches	2	approach	rural	245	248	**123**	**per approach**
BennBP	New roadway, 1-lane either direction	3.26	miles	rural	-48	-175	**-34**	**per mi.**
Rt100LaneAdds	Highway lane addition, from 1 to 2 in both directions	9.20	miles	rural	356	63	**23**	**per mi.**
NH Round-about	Conversion of stop- and yield-controlled intersection to a roundabout	1	each	rural	-1	8	**4**	**per intx**

For each of these applications, the number of vehicles was held fixed, so the results assume that no new vehicles (trucks or tow-plows) are added to the RSIC fleet. The effects of the new suburban roadway (CrCo) were the most significant, as expected since the road network is less connected outside of the urban core and there are fewer opportunities to devise an alternative set of efficient routes with the new roadway. In an urban core, adding a new roadway (ChPa) has less of an effect on RSIC effort because it is more likely that an existing route can be extended to cover it without the addition of much deadheading. Note also the negative effects of the addition of a bypass system for a new roadway in a rural micropolitan community.

Adding left-turn lanes to a rural intersection approach (Rt2Lefts) also had a significant effect on RSIC effort. These types of intersection improvements are common in rural and suburban areas where right-of-way is available for the addition of turning lanes, but their considerable effect on RSIC effort must be considered, especially in relation to the more moderate effect of converting a rural intersection to a roundabout. The impact of adding left-turn lanes might be moderated if the intersection being considered consists of four approaches that are all state-maintained roadways. However, in this case, as is true of many rural intersections, the major roadway is state-maintained, but the minor roadway is not, so only two of the four approaches are being modified and the state's responsibility is only for those two approaches, so a significant amount of deadheading is involved with getting both lanes plowed.

Table 14 contains a summary of the increase in vehicles allocated to the garage where each project is located.

Table 14 Summary of results of the Integrated RSIC Model applications for increased allocation

Project ID	Project Type	Quantity	Unit	Region Type	Low-Salt Storm	High-Salt Storm	Average Unit Increase (trks)	
CrCo	New roadway, 1-lane either direction	0.55	miles	suburban	1	0	**0.91**	**per mi.**
ChPa	New roadway, 1-lane either direction	3.56	miles	urban	1.5	1	**0.35**	**per mi.**
Rt2Lefts	New left-turn lanes, 2 of 4 approaches	2	approach	rural	0.5	0.5	**0.25**	**per approach**
BennBP	New roadway, 1-lane either direction	3.26	miles	rural	1	1	**0.31**	**per mi.**
Rt100LaneAdds	Highway lane addition, from 1 to 2 in both directions	9.20	miles	rural	1	2	**0.16**	**per mi.**
NH Round-about	Conversion of stop- and yield-controlled intersection to a roundabout	1	each	rural	--	--	**1***	**per intx**
*Assumes that a new vehicle is needed to maneuver through the roundabout								

As with the measured increases in effort, the effects of the new suburban roadway (CrCo) were the most significant, requiring almost 1 additional truck for each mile of new roadway. Lane additions were shown to have less of a need for additional trucks. Unless the new turn lanes are close to a garage, having a new vehicle deadheading through the network to reach the new lanes will rarely be efficient. Although the field data analysis was not able to identify the potential need for additional vehicles, it is possible that a roundabout will require a new vehicle simply because its configuration precludes the use of some heavier trucks.

Table 15 contains a summary of the increase in service time on the network, or the time it will take to complete a single pass across all state-maintained roadways.

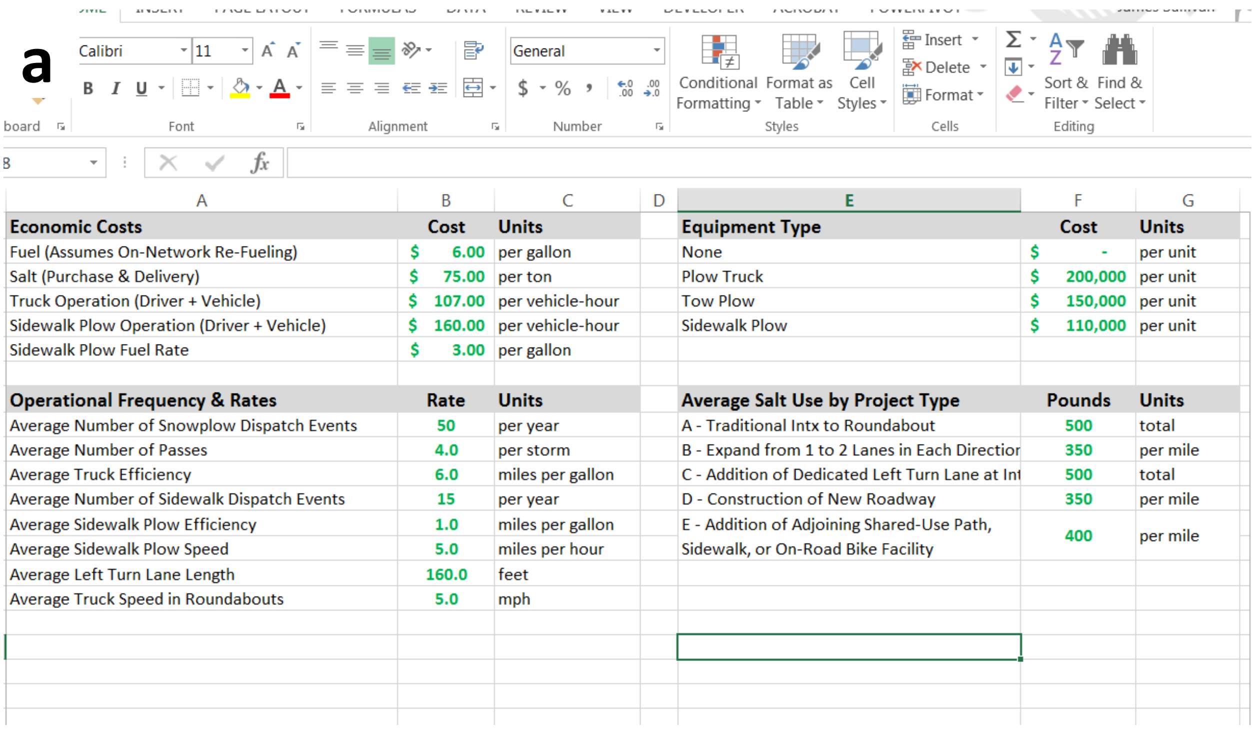
Table 15 Summary of results of the Integrated RSIC Model applications for increased service time

Project ID	Project Type	Quantity	Unit	Region Type	Low-Salt Storm	High-Salt Storm	Average Unit Increase (min.)	
CrCo	New roadway, 1-lane either direction	0.55	miles	suburban	8	35	**39**	**per mi.**
ChPa	New roadway, 1-lane either direction	3.56	miles	urban	9	38	**7**	**per mi.**
Rt2Lefts	New left-turn lanes, 2 of 4 approaches	2	approach	rural	14	0	**4**	**per approach**
BennBP	New roadway, 1-lane either direction	3.26	miles	rural	12	0	**2**	**per mi.**
Rt100LaneAdds	Highway lane addition, from 1 to 2 in both directions	9.20	miles	rural	5	16	**1**	**per mi.**
NH Round-about	Conversion of stop- and yield-controlled intersection to a roundabout	1	each	rural	--	--	**0**	**per intx.**

As with the other measures of RSIC burden, the effects of the new suburban roadway (CrCo) were the most significant, requiring almost 40 minutes of additional service time for each mile of new roadway. The other projects were shown to have a minimal effect on service time, especially in the high-salt storm scenario, when the longest service time was likely to have been at a garage that was elsewhere on the network, so the statewide service time did not change.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The results and findings of this research have implications for short-term funding allocations for RSIC operations staff and for long-term consideration of RSIC in the highway planning and design processes. The findings of this project provide defensible data for operations staff to advocate for increases in funding to offset the increased RSIC burden when a project is completed. The calculation tool described in Chapter 3.3 incorporates all of the results summarized in Chapter 4.7 into a MS Excel decision support platform, providing quick estimates of the monetary impact of a variety of major highway project types (Figure 19).

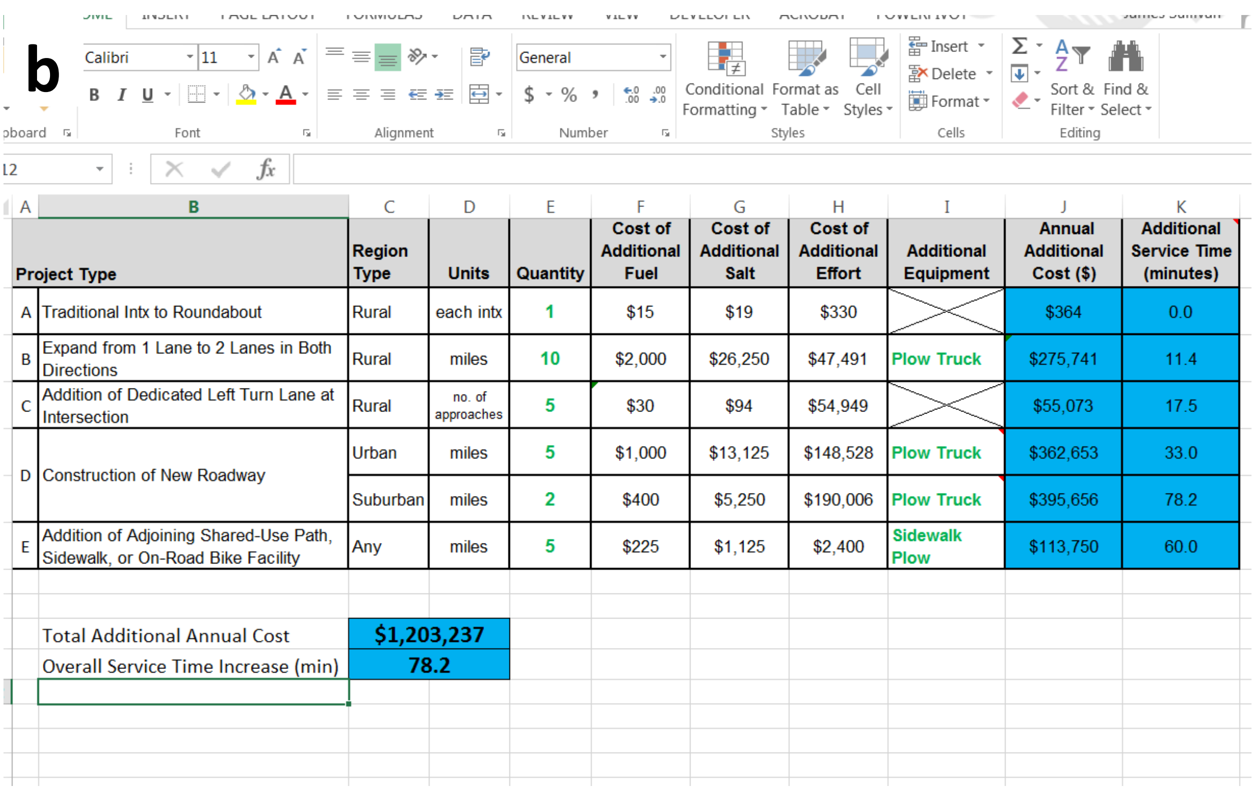


Economic Costs	Cost	Units
Fuel (Assumes On-Network Re-Fueling)	$ 6.00	per gallon
Salt (Purchase & Delivery)	$ 75.00	per ton
Truck Operation (Driver + Vehicle)	$ 107.00	per vehicle-hour
Sidewalk Plow Operation (Driver + Vehicle)	$ 160.00	per vehicle-hour
Sidewalk Plow Fuel Rate	$ 3.00	per gallon

Operational Frequency & Rates	Rate	Units
Average Number of Snowplow Dispatch Events	50	per year
Average Number of Passes	4.0	per storm
Average Truck Efficiency	6.0	miles per gallon
Average Number of Sidewalk Dispatch Events	15	per year
Average Sidewalk Plow Efficiency	1.0	miles per gallon
Average Sidewalk Plow Speed	5.0	miles per hour
Average Left Turn Lane Length	160.0	feet
Average Truck Speed in Roundabouts	5.0	mph

Equipment Type	Cost	Units
None	$ -	per unit
Plow Truck	$ 200,000	per unit
Tow Plow	$ 150,000	per unit
Sidewalk Plow	$ 110,000	per unit

Average Salt Use by Project Type	Pounds	Units
A - Traditional Intx to Roundabout	500	total
B - Expand from 1 to 2 Lanes in Each Directior	350	per mile
C - Addition of Dedicated Left Turn Lane at Int	500	total
D - Construction of New Roadway	350	per mile
E - Addition of Adjoining Shared-Use Path, Sidewalk, or On-Road Bike Facility	400	per mile



	Project Type	Region Type	Units	Quantity	Cost of Additional Fuel	Cost of Additional Salt	Cost of Additional Effort	Additional Equipment	Annual Additional Cost ($)	Additional Service Time (minutes)
A	Traditional Intx to Roundabout	Rural	each intx	1	$15	$19	$330		$364	0.0
B	Expand from 1 Lane to 2 Lanes in Both Directions	Rural	miles	10	$2,000	$26,250	$47,491	Plow Truck	$275,741	11.4
C	Addition of Dedicated Left Turn Lane at Intersection	Rural	no. of approaches	5	$30	$94	$54,949		$55,073	17.5
D	Construction of New Roadway	Urban	miles	5	$1,000	$13,125	$148,528	Plow Truck	$362,653	33.0
		Suburban	miles	2	$400	$5,250	$190,006	Plow Truck	$395,656	78.2
E	Addition of Adjoining Shared-Use Path, Sidewalk, or On-Road Bike Facility	Any	miles	5	$225	$1,125	$2,400	Sidewalk Plow	$113,750	60.0

Total Additional Annual Cost	$1,203,237
Overall Service Time Increase (min)	78.2

Figure 19 MS Excel Calculation Tool - User Data (a) and Decision Support Tool (b)

The tool provides an initial user-input worksheet (Figure 19a), which provides the user with the opportunity to enter specific costs and RSIC service parameters for the calculation of impacts. Default values are provided from defensible sources as described in Chapter 2.4 so the user does not need to make any inputs to get defensible results from the tool. The second worksheet (Figure 19b) requires the user to enter the specific details about the new projects being constructed in their state, region, or district. With these user-entered quantities, an annualized monetary cost is calculated, representing the net impact of the new project(s). An additional service time impact is also calculated, although this value does not contribute to the annualized monetary cost. It simply represents a loss of service quality that needs to be considered when evaluating total RSIC impacts. Note that this worksheet also allows the user, for certain project types and sizes, to select the option of purchasing new equipment – a plow truck, a tow plow, or a sidewalk plow. If new equipment is selected from one of the dropdown boxes, the costs of the new equipment are added to the annualized additional cost. A final system-wide total annual cost is calculated at the bottom of the worksheet, representing the total impact of all new capital projects entered above, along with a system-wide service-time increase, representing the highest increase of all the new capital projects entered above. A final worksheet is provided (not shown) in the tool showing the results from Chapter 4.7 for informational purposes, since these results provide the basis for how the calculation are made. We argue that the tool should be used in the early stages of capital project development to estimate the need for additional RSIC resources such as trucks, salt, fuel, and operator hours to properly maintain new infrastructure once the capital project is completed.

These findings also provide a strong argument the increased need to involve RSIC operations staff in the highway planning and design processes for major capital projects. The ultimate long-term goal is for the geometric design of highways to fully consider the impacts on all operations & maintenance needs, including RSIC. Table 16 provides a list of the general considerations that are recommended for the new capital project types analyzed in this project.

Table 16 RSIC Considerations and Recommendations for Design of New Capital Projects

Project Type	Description	Considerations	Recommendations
Intersection Improvements	Addition of left- or right-turn lanes	Seasonal traffic flows – whether the turn lanes are needed in winter, or if RSIC can be relaxed and the turn lanes left uncleared	Incorporate wide turnarounds leaving intersections on each departure, especially non-state-maintained approaches
	Conversion of traditional stop- or yield- control to a roundabout	Roundabout traffic behavior under snowy or icy conditions, or with plowed snow built up along the edge, potentially restricting visibility and shoulder clearance	Incorporate wide turnarounds leaving the roundabout on each departure, especially non-state-maintained approaches

Project Type	Description	Considerations	Recommendations
New roadway construction	One lane each direction	Connections to non-state-maintained facilities Network connectivity effects for routing	Use wider lanes and shoulders where winter traffic requires that the roadway be kept clear Design roadways with smooth transitions from other state-maintained facilities to facilitate heavy vehicle movement around turns Reduce or eliminate the need for deadheading when servicing state-maintained facilities by ensuring route connectivity, or provide adequate turnarounds.
Roadway expansion	One lane each direction to two lanes each direction; two lanes each direction to three lanes each direction		Use wider lanes and shoulders where winter traffic requires that the roadway be kept clear Reduce or eliminate the need for deadheading when servicing state-maintained facilities by ensuring route connectivity, or provide adequate turnarounds. Avoid adding lanes to highways in rural areas where network connectivity is poor, or where distance to the nearest district garage is far

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APPENDIX A
SURVEY RESPONSES

From: Peters, Thomas (DOT) [mailto:tom.peters@state.mn.us]
Sent: Friday, August 28, 2015 8:15 AM
To: James Sullivan <James.Sullivan@uvm.edu>
Subject: Re: [SNOW-ICE] Last call for Case Studies Needed for Snow and Ice Control Project

Jim,

MnDOT will participate and look to provide some good examples.

Tom Peters
Maintenance Research Engineer

From: Anderle, Phillip [mailto:PAnderle@indot.IN.gov]
Sent: Monday, August 31, 2015 7:20 AM
To: Brooks, Jeffrey <JBROOKS@indot.IN.gov>
Cc: James Sullivan <James.Sullivan@uvm.edu>
Subject: RE: [SNOW-ICE] Last call for Case Studies Needed for Snow and Ice Control Project

Can you give Jim the details?

From: Brooks, Jeffrey
Sent: Friday, August 28, 2015 3:10 PM
To: Anderle, Phillip
Subject: RE: [SNOW-ICE] Last call for Case Studies Needed for Snow and Ice Control Project

I cannot identify any projects that would include roundabouts, however, we have some major construction taking place on US 31 corridor between I-465 and Westfield that will have a significant impact to SIC. It would be a good candidate.

J.D. Brooks
Greenfield District Highway Maintenance Director
32 South Broadway
Greenfield, IN 46140
Office: (317) 467-3484
Cell: (765) 617-8735
Email: jbrooks@indot.in.gov

____

From: Robert Lannert [mailto:mosnowking@aol.com]
Sent: Monday, August 31, 2015 4:04 PM
To: James Sullivan <James.Sullivan@uvm.edu>
Subject: RE: [SNOW-ICE] Last call for Case Studies Needed for Snow and Ice Control Project

This is Bob Lannert, the inventor of the TowPLow and retired MoDot Engineer. I have now personally worked in over 16 states.

I am not sure if these problems fit your study but these impact DOT operating costs in snow removal costs. Some are old problems, some new:

1. Raised “snow plow-able” center and edge markers dramatically increase blade costs. Carbide blades previously last up to 3 winters. Now, some only last one storm due to carbide fracturing by dynamic impact upon so called plow-able markers.

2. There is a major difference in plowing rumble strips which have been formed into concrete and rolled into asphalt vs. those which are rotomilled into the pavement. The first extrudes material upward which then react with plow blades.

3. The construction of building additional lanes and a center wall by filling and obliterating the median has caused the agency to plow all snow to the right which blocks traffic when performed compared to plowing some left into the median and some right to right ditch. This practice of using the median has caused not only the need to plow more lanes but further complicated how the work was performed. Note some states have ruled that they cannot plow against the median barrier and form a ramp. Designing taller walls and storage on left side would help to allow some snow to go left.

4. There are some areas where lanes have been added and the cross section slopes dramatically change. The problem is that all snow plows need to operate on consistent pavement and not on two different plains. This has cause major blade wear and additional costs to plowing.

5. Some design geometrics does not provide ANY discharge and storage areas for snow. This causes discharged windrows of snow to be left across other lanes without any resolution.

These are just quick notes of what I have seen the last 10 years….

Bob Lannert
Technical Support Engineer
Snow King Technologies consultant to
Viking Cives Midwest
Cell 573-690-7600

CLEAR ROADS

research for winter highway maintenance

Lead state:

Minnesota Department of Transportation
Research Services
395 John Ireland Blvd.
St. Paul, MN 55155