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Road Salt in Maine: An Assessment of Practices, Impacts and Safety

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The views and opinions expressed in this report are solely those of the Margaret Chase Smith Policy Center and the individual authors. They do not represent those of MaineDOT or any other individual or organization that has provided information or assistance.

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Executive Summary

This report presents the results from a research project by a team from the University of Maine, in cooperation with the Maine Department of Transportation (MaineDOT), that examines the use of road salt in Maine for winter travel safety. It summarizes winter maintenance practices, changing winter weather patterns, environmental impacts and costs, and winter road safety. This report follows a 2010 report (Rubin et al. 2010).

In the 10 years since our previous study, research in Maine and nationwide shows increasing salt accumulation in both freshwater and groundwater environments. The MaineDOT requested this study to more closely examine the trends in Maine and the impacts we may experience from warming winters and changing weather patterns. We collected data from MaineDOT, the Maine Turnpike Authority (MTA), and Maine's municipal governments on winter road maintenance practices, materials (e.g., salt) and costs.

We look at road safety in terms of factors that impact crashes in winter driving. To analyze road safety and the relationship between winter weather and crashes, we examined data from all police reported crashes from 2015–2019 in Maine. This is matched with daily weather data from weather stations throughout the state.

We examined the relationships between wintertime weather and salt use in Maine over the past three decades. Recent changes in the weather and climate patterns are assessed for their long-term trends. A suite of seasonal weather indices used by transportation management agencies are analyzed for sensitivity to weather/climate patterns and potential use for planning and decision-making linked to salt use and application. The analysis provides a quantitative basis to understand the salience of changing winter weather patterns to salt use and transportation infrastructure planning and decision-making. Our analysis offers insights regarding future expectations in a changing climate.

The evaluation of environmental impacts of from salt use is based on geospatially distributed records from well testing to assess the prevalence of chloride contamination in groundwater wells. We derive estimates of the risk of chloride contamination at the town level, as well as their potential relationship with soil hydraulic conductivity, presence of faults in bedrock and other location specific factors. We provide some insight into what to expect in the future given climate change.

The state of Maine has 45,586 miles of public roadway, more miles per person than any other New England state, see Table 1 (p. 10). This mileage is maintained by MaineDOT, Maine Turnpike Authority, and municipalities and counties. MaineDOT maintains approximately 4,100 centerline miles in winter, 18% of the total roadway, which it divides into three categories of priority. The Maine Turnpike Authority maintains 109 centerline miles, all high priority. The remainder of the mileage is maintained by Maine's 483 towns and cities, 10 counties, and 3 reservations with winter road maintenance responsibility. The municipal mileage amounts to approximately 81% of the state's total road mileage.

We collected data from MaineDOT, the Maine Turnpike Authority and Maine's municipal governments on winter road maintenance materials (e.g., salt) and costs. Municipal practices vary considerably, and we surveyed municipalities to compile a more complete picture of practices, materials used, and costs. For perspective, we briefly highlight winter maintenance practices in selected states. We look at road safety in terms of factors that impact crashes in winter driving.

Best management practices (BMPs) for winter road maintenance are widely available. *Anti-icing* is a principal BMP. Most Maine state roads are maintained using an anti-icing strategy (see the Glossary of Terms, p. 92). MaineDOT currently uses this approach on almost all state roads, treating roads before ice and snow are able to bond to the roadway. The MTA employs an anti-icing approach on the entire turnpike. Some 28% of Maine municipalities in our survey say they employ anti-icing while the remainder use the more traditional approach of *de-icing,* which involves spreading sand with some salt in it. *Pre-treating* roads with brine as a component of anti-icing requires special equipment for the application of liquids. Neither MTA nor MaineDOT currently pre-treats with brine. About 12% of municipalities reported pre-treating their roads, though they did not specify the use of brine. Statewide, 71% of towns surveyed report that they never wet their salt before spreading.

Communities within the northern DOT region and Maine's smaller communities are more likely to use the traditional method of spreading sand with some salt in it, while the southern DOT region has the highest rate of communities using an anti-icing approach with salt. While the majority of winter maintenance occurs on roads, 71% of municipalities also include sidewalks and parking lots in their operations. All MaineDOT and MTA road staff receive training on best practices for winter maintenance. Some 69% of communities surveyed reported that their drivers receive training on best practices for winter maintenance. Localized weather forecasting can allow specific treatment of roads; MaineDOT and MTA benefit from the use of localized forecasting, as do some larger municipalities.

By far the most widely used material on winter roads in Maine is rock salt (sodium chloride, NaCl) due to its cost-effectiveness and ease of handling. The total bulk salt purchased in the state in 2019–2020, from distributors, amounts to approximately 535,000 tons. We independently calculate salt totals by combining salt purchases from MDOT, MTA, and municipal governments. Using this method, we estimate approximately 493,000 tons, or about 42,000 tons or 9%, less than the bulk amount purchased. This 9% difference is likely explained by the non-road use of salt on commercial and industrial parking lots and other private uses**. This means that Maine uses roughly 787 pounds of salt for every Maine resident, or 11 tons per lane mile per year.** In addition to sodium chloride, other commonly used chemicals for snow and ice control that lower the freezing point of water (i.e., they work at lower temperatures than sodium chloride or have other desirable properties) include calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$). Potassium acetate (KA) and calcium magnesium acetate (CMA) are effective but lesser used. Sand is commonly used for traction on municipal roads, but it has no ice-melting properties and is rarely used on MaineDOT- or MTA-maintained roads.

We estimate that clearing winter roads statewide costs Maine $155 million dollars, or $114 per resident. This amount does not include non-budgeted costs for environmental impacts or corrosion of infrastructure and vehicles, nor does it include remediation costs of wells contaminated from road salts. Under state law, MaineDOT is obligated to resolve well claims for private water supplies that are destroyed, or rendered unfit for human consumption, by constructing, reconstructing, or maintaining a highway, including the use of salts for winter road maintenance (mobility) (Maine Revised Statutes 1971). MaineDOT has spent approximately $5.3 million since 2006 to investigate, assess, and resolve well claims.

Changes in winter road maintenance practices could provide an opportunity for cost savings. Any changes will need to be balanced with levels of service that the public has come to expect. The clear roads resulting from this salt use contribute to high levels of safety and mobility. But the consequences of our collective road salt use show up in reduced water quality of some streams, contaminated wells, infrastructure and vehicle corrosion, and state and municipal budgets. As salt use increases so do its impacts. One way to reduce salt is to change drivers’ expectations of travel during a storm.

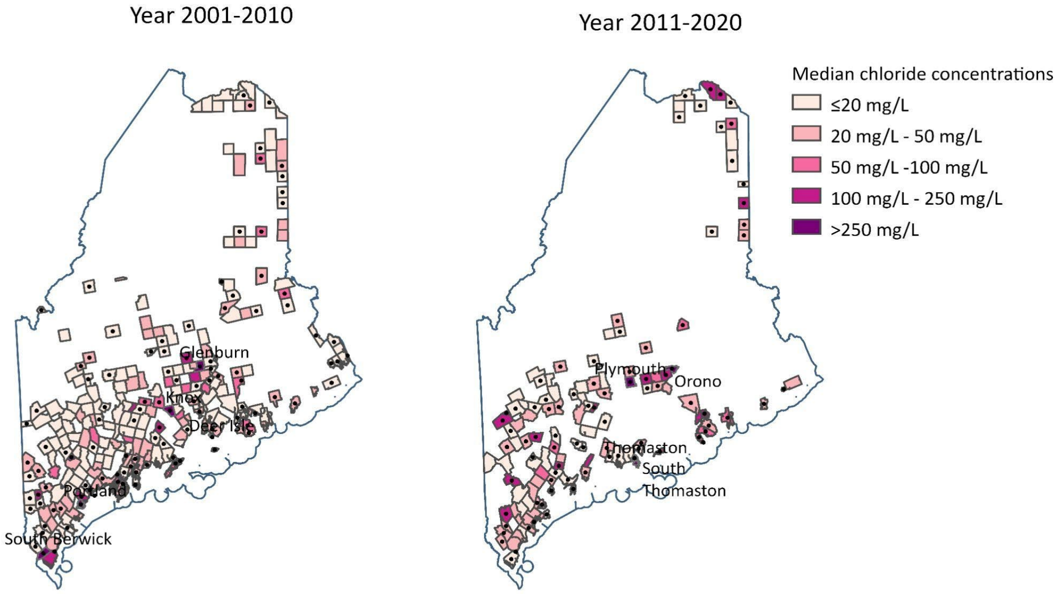
Impacts

There is ample evidence that salt (NaCl) is increasing in the aquatic environment in both the short term (months) and the long term (years). Winter road maintenance is a significant source of the total chloride loading to fresh waters. Short-term effects are directly related to the seasonality of salt use, with peak levels occurring in spring and fall. Although most chloride is exported, some accumulates in watersheds over time. Several long-term studies find evidence of an increasing chloride trend. Twenty streams in Maine are now noted on the Maine DEP’s list of chloride impaired urban stream watersheds (MDEP 2019). Most of these are located in developed urban or suburban areas with significant amounts of impervious pavement or roadway. Our survey of municipalities reports that among responding towns, 16% report some municipal areas that require special practices for winter maintenance, such as wetlands or public water supply. Additionally, 22% of respondents reported that they have had a well claim for salt contamination in their jurisdiction.

The Maine Well Database contains records from 1990 to 2021 (see *Well Contamination in Maine* and the data limitations therein, p. 30). These data show that the general spatial distribution of wells appears to be linked to the population density, as well as factors such as presence of water supply systems. Since nearly 40% of the residents of Maine use private wells for water supplies, water quality testing affords useful information to create baselines to assess presence of various chemical constituents.

The median chloride concentration in groundwater in Maine towns over two periods (2001–2010) and (2011–2020) are presented in Figure 1. Towns with median chloride concentrations above 250 mg/L are labeled. The town of Durham in Androscoggin showed the maximum number of contamination cases of 13 for this period. During 2011–2020, 15 towns had at least one well with a chloride concentration above the Secondary Maximum Contaminant Level. South Thomaston in Knox county showed the highest number of contaminated wells (4).

Figure 1: Median Chloride Concentration in Maine Towns



During the first decade (2001–2010), towns of South Berwick, Portland, Knox, and Glenburn (left map in Figure 1) showed median concentrations of chloride above 250 mg/L. For the latter period (2011–2020), Thomaston, South Thomaston, Plymouth, and Orono had contamination levels of chlorides. Improved sampling that spans communities and includes more towns can help to accurately identify the towns at risk of chloride contamination.

Once contaminated by high chloride levels, surface and ground water will only recover after the source of chloride contamination is eliminated, which can take decades. Maintaining water quality in Maine for the long term must include reducing the amount of chloride that we put into the environment.

Shallow wells are more susceptible to contamination from road salts, and the wells most likely to be affected are generally within 100 feet (30 m) down-gradient of the roadway in the direction of groundwater movement. However, local biophysical factors such as the soil ion exchange capacity, hydraulic conductivity, and location of water table play mediatory roles in the transport of road salt to groundwater, meaning that the prevalence of chloride contamination in wells across Maine cannot be directly inferred from spatial patterns of road salt application.

Salt used for winter road maintenance, beneficial for public safety, has a well-documented impact on the infrastructure of concrete bridges, roads, and sidewalks as well as corrosive effects on vehicles. Neither the extent of infrastructure deterioration in Maine nor its financial impact were calculated as part of this study.

Promising Approaches to Change

The experience of other states may offer lessons for Maine. The state of New Hampshire has responded to an increasing number of chloride-impaired streams and rising chloride concentration in groundwater by implementing a statewide program to provide training and liability protection to winter contractors. Connecticut has followed the model of New Hampshire's Green Snow Pro program, offering training, but without the liability limitation, for applicators. Minnesota takes a more high-tech approach to winter road maintenance and is a leader in chloride reduction efforts, with a well-developed network of Road Weather Information Systems and Automatic Vehicle Location Maintenance Decision Support System supporting Minnesota DOT's liquid anti-icing program. In New York, the governor recently signed a bill establishing a salt reduction task force and a 3-year test program will be conducted on all state-owned roadways within the Adirondack Park. New York has also proposed a road salt applicator training program, similar to New Hampshire's Green Snow Pro. A New York state pilot program for salt reduction is showing promising results for cost savings in some Adirondack communities, while individual municipalities there are having notable successes working to reduce road salt use with new equipment, new tracking techniques, the use of brine, and training.

In Maine, the Long Creek Watershed Management District (LCWMD), in a strategy similar to the Adirondack municipalities, is implementing a pilot program that focuses on the cooperation of multiple stakeholders, applicator training, full cost accounting, and salt reduction. Results from the LCWMD pilot program may inform Maine's salt policy.

Maine's Changing Climate

Wintertime road conditions comprise a complex array of weather phenomena, ranging from icing, frost, frozen rain, to black ice, to name a few. Thus, the amount and timing of salt application on roads is closely linked to winter weather severity.

A key finding from statistical analysis of annual salt use in Maine and three widely used winter weather indices is that for the past 30 years, AWSSI, the model used by MDOT, which is based on temperature and snowfall, shows satisfactory performance and explains 80% of annual salt use variations. Furthermore, the two other indices also show moderate statistical relationship with the salt use record for the state of Maine. Since a diversity of winter conditions have salience towards transportation concerns and salt application, detailed analyses based on winter weather triggers (snow days with different temperature conditions and frost days) are also analyzed and shown to have a statistically significant relationship with road salt use. The suite of weather indices used for analysis in this report offers a comprehensive view of the variability and changes in winter conditions and their relative importance for different regions of the state. The observed trend in the AWSSI index, accumulated snow, and decreases in the accumulated freezing degree days, show varying spatial extents. However, the wintertime weather patterns have changed significantly, both towards high variability and trends in episodic and seasonal statistics of winter weather. See the full analysis in our section on *Maine's Changing Climate*, p. 40.

Traffic Safety

The outcomes of this study provide insights to the safety analysts, practitioners, agencies, and the Department of Transportation in Maine or similar states to better understand the weather factors impacting frequency of lane departure crashes in Maine. It also analyzes various factors impacting the severity of crashes. The models were developed for four rural facility types (i.e., minor collectors, major collectors, minor arterials, principal arterials—Interstates). The results help to allocate necessary funds to develop countermeasures or improve safety across the state. The full analysis is in the *Traffic Safety Analysis and Winter Weather* section (p. 61). A few highlights of the lane departure crashes follow.

Approximately 67% of all lane departure crashes from 2010 to 2019 occurred during the winter period (November through April). This includes 62% of all truck-involved crashes (also, the frequency of truck-involved crashes has substantially increased from 2016–2019). Using Federal Highway Administration data (FHWA), the winter period accounts for yearly average economic loss values of $618 million during the 2010–2019 period, with a yearly average of over $309 million from fatalities alone (MaineDOT 2018). While fatalities are a primary concern, approximately 63% of all lane departure crashes result in property damage only, 37% result in injury (A+B+C crashes), and 1.2% result in a fatality.

Drivers aged 20–24 have the highest crash counts of any age group. The number of licensed drivers aged 65+ continues to grow. In 2010 they accounted for 18% of the total licensed drivers; in 2019 they accounted for 25%. At the same time, the number of young drivers (age 16–29) continues to fall from 20% of all Maine licensed drivers in 2010 to 17% in 2019.

As explained in detail in the safety section, our analysis shows that as the number of days with more than 1 inch of precipitation increases by 1% from the average, the expected winter monthly crashes increase by 0.09% on interstates, 0.02% on minor arterials, 0.01% on major collectors, and 0.02% on minor collectors. When this precipitation is snow (> 1 inch), the expected average winter monthly crashes increase by 0.5% on interstates, 0.05% on minor arterials, 0.04% on major collectors, and 0.03% on minor collectors. In addition, during the non-winter period, the frequency of lane departure crashes on interstates is impacted by precipitation.

In addition, our results show that crashes involving older drivers (65+) have an increased or risk of major injuries (compared to property damages) of 327% on interstates, 150% on minor arterials, 345% on major collectors, and 366% on minor collectors. The failure to use a seatbelt showed to be the most influential variable in all models. **When drivers or passengers did not use a seatbelt in a crash, the chances of the crash resulting in major injuries (compared to property damages) is 27.3 times higher on interstates, 24.1 times higher on minor arterials, 22.7 times higher on major collectors, and 14 times higher on minor collectors.**

During the *winter period* (November–April) compared to the non-winter period, the results show that, given a crash, the odds of fatal/major injury crashes decreased by 82% on interstates, 65% on minor arterials, 75% on major collectors, and 48% on minor collectors compared to property damage only crashes. Moreover, the models show that crashes that occur on snow days with snowfall (> 1 inches) have decreased odds of serious injury (compared to property damage only crashes): 78% on major collectors and 71% on minor collectors. For crashes that occur on surface conditions that are not dry pavement, we found an increased chance of major injuries (compared to property damages): 70% on interstates, 63% on minor arterials, and 46% on minor collectors.

For all roadways, during both winter and non-winter periods, the posted speed limit is positively correlated with monthly crashes; as the posted speed limit increases, the number of monthly lane departure crashes increases. The width of the left and right shoulders showed a negative correlation with monthly crashes for all facilities for both seasonal periods. As snow is plowed, it accumulates on the shoulder with each storm (unless located in a hazardous location such as on bridges). This may explain why the impact of shoulder width on crashes is larger during the non-winter period compared to the winter periods. The results show that the paved shoulder can reduce the number of crashes during the winter session.

Recommendations

Maintaining wintertime mobility while reducing fiscal and environmental costs requires the careful balancing of many factors. In general, we applaud MaineDOT, MTA and municipal governments for their thoughtful approaches to winter maintenance practices. That said, we do have some suggestions for consideration.

First, the public needs to better understand the fiscal and environmental costs of winter maintenance. We suggest that all levels of government (MaineDOT, MTA, municipal) need to better articulate the tradeoffs for different levels of service. Communities may well make different choices reflecting their own set of values and needs, just as they do with school and police budgets. From our survey of municipalities, we know that towns can have winter maintenance costs per lane that differ substantially. Some of this is explained by population density, geography, sidewalk clearing, and, in urban areas, the need to haul snow, but not all. We suggest that towns take a deliberative approach to reexamine their winter maintenance needs. Savings, both financially and environmentally, may be available; there is no one-size-fits-all solution.

Building on the excellent work by individuals in state and municipal governments, we recommend that Maine develop a statewide chloride reduction plan that identifies and prioritizes salt reduction in regions with environmentally sensitive areas and those areas already showing impact from chlorides. Complementing such a plan, we suggest MaineDOT and MaineDEP increase their monitoring of chlorides in water bodies and make this information easily accessible to the public via a data dashboard, which would also contribute to the goal of public awareness.

Complementing this would be an annual salt symposium involving a range of stakeholders and the public.

Wintertime weather indices can offer useful guidance regarding frequency, intensity, and duration of storm conditions, and also allow planning and decisionmaking regarding the use of road salt. Given the changing climatic baselines, we recommend a detailed assessment of hazardous weather conditions, in particular based on hourly weather data to determine how storms mix snow, rain, freezing rain and sleet, and frost conditions throughout the state.

Because of the interlinked nature of salt use and its migration into both surface and subsurface waters, we suggest the formation of an interagency taskforce to facilitate communication, and information and data sharing between MaineDOT and MDEP. We observed conscientious attention by professionals in each agency, but we also observed areas where additional collaboration could be useful. This task force should include municipal governments and should first focus on salt reduction in areas already impacted.

MaineDOT's winter maintenance training program for municipalities through the Local Roads Center should be strengthened through greater funding, particularly allowing it to expand and strengthen training at the local level. Funding sources should be identified to help underfunded municipalities upgrade their equipment, training, and winter practices. The aforementioned areas of the state with higher salt use, higher percentage of impervious cover, or already identified water quality impairments should be the focus of specific attention for salt reduction strategies, whether through the local roads program or a statewide taskforce. Chloride monitoring should be implemented statewide for areas not already known to be affected.

A majority (70%) of the towns responding to our survey reported that they have not defined and communicated a policy on the level of service for their roads. This suggests a need to better communicate, particularly at the municipal level and for non-highway state roads, the levels of service on roads and the associated costs of winter maintenance.

Maine could benefit from stronger connections between university research, environmental monitoring, and road practitioners. An examination of the partnership structures in practice in other states in New England, at both state and municipal levels, may offer models for collaborative partnerships in Maine.

In our survey of municipalities, responding towns were relatively evenly split between those using municipal crews and those using private contractors. Municipalities with smaller populations were more likely to use contractors for winter maintenance. Expanding state training options and best practice recommendations to these contractors may be warranted.

The survey in this study focused on identifying municipal practices. Further effort should be made to identify the practices, salt use, and concerns of private contractors who are hired by municipalities and contractors who maintain non-road areas (parking lots and private roads) in Maine. Then the state could determine if it would benefit from implementing a winter maintenance contractor training program, with or without limited liability, following lessons learned from New Hampshire's and Connecticut's programs. A statewide organization such as the Maine Municipal Association could help facilitate communications among municipalities statewide, including providing training for town managers on the impacts and tradeoffs of salt application and recent developments and policy approaches. Importantly, a pilot program implemented by the Long Creek Watershed Management District (LCWMD) should be closely watched and, if merited, replicated in other areas of the state. Evidence from NY municipalities that have followed this program shows that through up-front investment and a multi-year commitment, this approach can lead to both salt reduction and cost savings.

A primary goal of this analysis was to determine the impact of various weather factors on *lane departure crashes*. For all four facilities, the number of days in a month with more than 1 inch of precipitation or snowfall is positively associated with the frequency of crashes. Different countermeasures should be considered to help decrease crashes on these days, including the use of additional signage, news reporting, and education about the danger, especially with respect to driving speed, on such days. In rainfall, the risk of hydroplaning, and in snowfalls, the risk of slippery conditions and driver error increases, which could result in higher crash frequencies. The state may consider reducing the adverse impact of these factors by imposing higher standards for tire condition. The province of Quebec requires snow tires on all vehicles from December 1st to March 15th. Additional research could examine the experience of Quebec for the safety impacts of the requirement for snow tires.

Precipitation also alters visibility. Therefore, we recommended the use of proper messaging to ensure decreased driving speeds on high precipitation days. During the non-winter period, both interstates and major collectors showed increased crash frequency on days with maximum rainfall. Similar countermeasures to those stated earlier such as increased signage or enforcement to decrease speed should be considered. Finally, more safety education and awareness campaigns are recommended during storm events.

In terms of *geometric road features* that positively affect crashes, curve presence showed an increased crash frequency on minor arterials, major collectors, and minor collectors. Countermeasures for these locations include messaging or signage to make drivers aware of the upcoming curves, speed reduction at these locations, along with improvement to the infrastructure or roadway facility. Countermeasures to reduce lane departure crashes include the installation of rumble strips as well as barriers and guardrails. This analysis only considered the presence of a curve as a variable in the models; however, we recommend additional research about the curves such as radius, friction, or elevation to add to the model to determine hotspots. We also found that higher speed limits are associated with higher crash frequencies, and speed limits in high crash locations should be reevaluated as a potential way to reduce lane departure crashes at these locations. Due to limited data, the impact of rumble strips on lane departure crashes was not identified in this analysis. Additionally, the Road Weather Information Systems could include more accurate and reliable weather data for road segments.

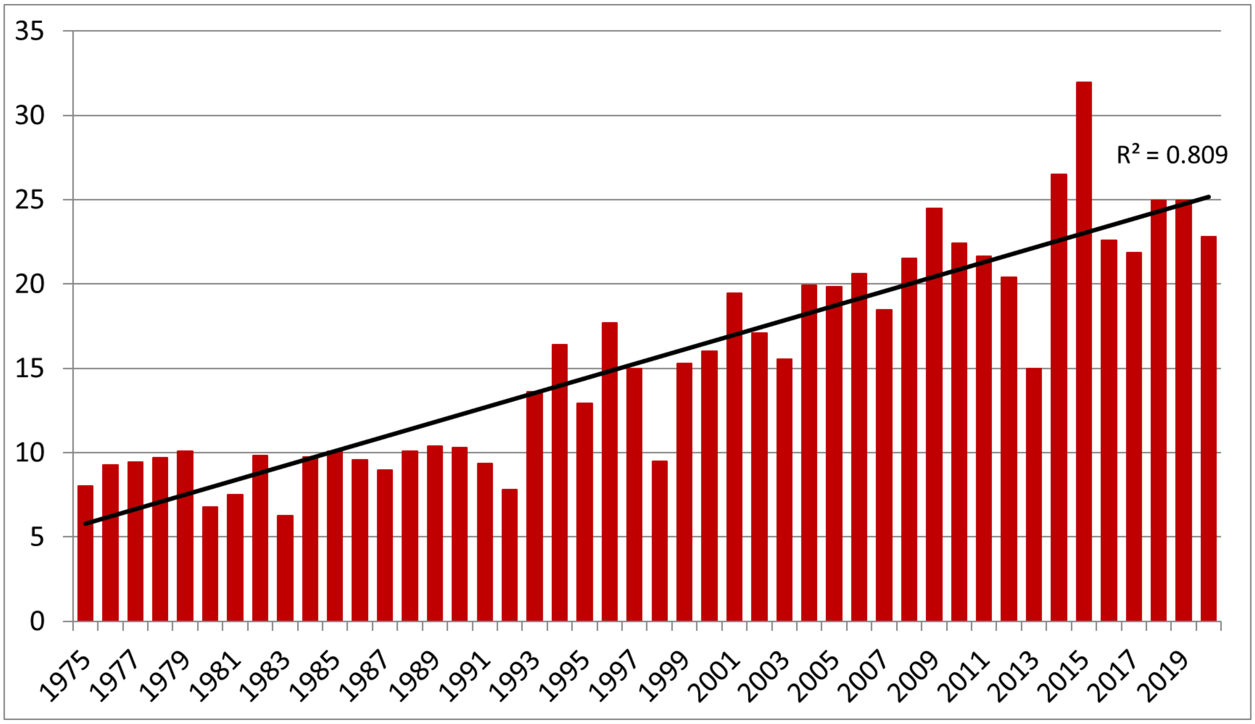
Finally, our analysis considered two time periods, the winter period, from November to April, and the non-winter period from May to October. By separating these two periods, we indirectly accounted for the greater darkness during the winter period. It is, however, recommended to study the impact of time of day (or darkness) in frequency of lane departure crashes in the future research.

Introduction

This report examines winter maintenance practices in the state of Maine through their costs, environmental impacts, and safety. We look at materials and current operations on state and municipal roads, and we summarize their impacts, present an analysis of changing weather patterns with regard to seasonal road maintenance, and examine winter road safety. In the 10 years since our previous study of road salt in Maine, there is evidence of increasing salt use and increasing accumulation of chlorides in surface waters and groundwater in the Northeast.

Road salts, primarily sodium chloride (NaCl), were first used in the 1940s to help clear winter roads of snow and ice. Since then, U.S. salt consumption for de-icing winter roads has been steadily increasing (Figure 2). In 2020, highway de-icing accounted for about 43% of total salt consumed, totaling about 23 million metric tonnes (USGS 2021). Maine has 45,586 lane miles of winter roads and 1,047,893 licensed drivers (BMV 2020).[1] Maine used approximately 535,852 tons or 1,071,704 thousand pounds in 2019–2020. This rate is equivalent to 787 pounds per person or 23,510 pounds per lane mile.

Figure 2: NaCl Salt Used for De-icing in the United States (million metric tons)



Road salt is effective in helping clear roads and provide safe travel, facilitating commerce. Our section on *Traffic Safety Analysis and Winter Weather* (p. 61) takes an in-depth look at road safety trends and accidents in Maine. We see that factors such as drivers' age, weather, road design, and road type all influence the number of crashes and fatalities. Road salt also runs off roadways after

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[1] Some drivers likely have more than one license, i.e., both a class A motor vehicle license and a motorcycle license.

application, impacting streams, groundwater, and infrastructure. Our section on *Impacts of Salt Use* (p. 4) summarizes the environmental impacts that are of particular concern because once salt becomes dispersed through groundwater or surface water, there is no natural process for removal; surface waters can flush more quickly, depending on flow, though often resulting in accumulation into groundwater.

Changing Expectations

During the past 60 years of increasing use of road salt to clear roadways in winter, public expectations have changed. Studies of driver behavior indicate that as winter road maintenance practices improve, the traveling public expects to drive at the posted speed limit sooner after a storm and expects to have bare pavement within hours (Veneziano 2019). The higher the level of service achieved by using best practices, modern equipment, and new materials, the higher the expectations are for maintaining it. The public is attentive to direct costs incurred in winter maintenance for this level of service, such as equipment, labor, and salt, but the indirect costs of environmental impacts are harder to quantify and understand, and they are rarely communicated to the public directly.

Fluctuating weather patterns in recent years in Maine means more winter thawing and freezing rain, and warmer winters. These changing climate conditions have an additional impact on winter road maintenance and on our use of road salt, which we discuss in our section on Weather Severity and in our section on Safety Analysis. Charting a path forward for winter maintenance in Maine requires an understanding of current practices. We look at operations, materials, and costs statewide by examining the practices of MaineDOT, Maine Turnpike Authority, and Maine's municipalities in our section on Winter Practices.

Although Maine is a rural state, we already have watersheds with chloride impairment in areas of high road density or large percentages of impervious surface. Balancing cost, environmental impact, safety, and transit becomes a task for policy makers. Even following best management practices, local decision-making will impact road salt application rates and practices. For some jurisdictions, cost is the overriding consideration, while for others, it may be environmental impact or driver safety.

Best Management Practices

The most recent guidance for winter maintenance and manuals for best management practices (BMPs) are readily available in the transportation literature (Fay, Shi, and Huang 2013; Shi and Fu 2018). BMPs aim to optimize the use of salt to limit both cost and environmental impact while maintaining safe roads without restricting travel and transit. Guidelines for winter road maintenance are available at the national level for state DOTs and at the state level encompassing municipalities. There are manuals with focus on specific practices, such as anti-icing; with focus on the environmental impact; with focus on training applicators; specifically, for sidewalk and parking lot management; for guidance in applying sand on rural roads; and for proper storage of salt and sand. Some of these are shown in *Appendix 2: Further Resources* (p. 106).

BMPs include anti-icing, pre-wetting, proper calibration of equipment, using automated spreader controls to vary application rates, proper salt storage facilities, and road condition and weather information systems. In addition, equipment such as live edge blades and flexible plow blades can reduce the amount of salt needed, while pavement temperature sensors can improve efficiency (Kelly, Findlay, and Weathers 2019). Some BMPs make the most effective use of materials and equipment, while others recommend changes in behavior. Behavioral changes include adjusting levels of service to current conditions, clearly communicating road conditions and expectations to drivers, and reducing speed. Newer cars, improved safety features, and busy schedules mean people increase their expectations for travel during and immediately after storms.

BMPs for Maine were developed in 2015 by stakeholders as part of the Maine Snow and Ice Control Best Practices Working Group, which included MaineDOT, MTA, MaineDEP, and others and distributed as a field manual. This manual includes a detailed explanation of administrative practices, such as defining level of service and forecasting, guidance for selection of materials, and BMPs for material application, equipment, and storage, and an explanation of the impacts of winter road maintenance. Some of the primary application BMPs relevant for Maine are anti-icing, pre-treating, pre-wetting, calibration, and use of weather information and training.

The two primary methods for removing ice and snow from a road surface are *de-icing* and *anti-icing.* De-icing is conducted after a snow event to break the bond of snow and ice that have already attached to the road. Anti-icing operations are conducted before snow events to prevent snow and ice from bonding to the pavement, so they can be easily removed with plows. Anti-icing involves application of liquids or pre-wetted solids in advance of snowfall. Anti-icing uses calibrated equipment to spread salt early in a storm to prevent the snow and ice from bonding to the road. Snow begins melting on pavements as soon as it comes in contact with the material, rather than packing onto the roadway as it does with the traditional approach of de-icing. Pre-treating roads to achieve anti-icing can be accomplished in two ways: (1) using dry or pre-wetted rock salt applied early in the storm; and (2) applying salt brine directly on the road before a storm. Research shows that under the right conditions, liquids are effective in pre-treating roads and can reduce both the amount of material used (in some cases up to 50%) and also reduce operational effort (Clear Roads 2015). The use of liquids requires modified equipment for application and additional storage for liquids. The selection of specific de-icing methods is influenced by geographical location, roadway conditions, weather, amount of snow or ice, and cost.

Studies have found that when salt is applied dry (without pre-wetting) 30% ends up outside the roadway (i.e., in the ditch) while when applied pre-wet, only 4% ends up in the ditch (Nixon and DeVries 2015). Pre-wetting salt while spreading is a BMP that is followed by all of MaineDOT, and MTA. In our survey, only 29% of Maine municipalities report pre-wetting their salt always or sometimes.

Calibration of equipment is a recommended practice to avoid over-salting. MaineDOT employs this practice, and MaineDOT's Maine Local Roads Center training program teaches calibration techniques in its training program for municipalities. Recent experience from New York State recommends monthly calibration of equipment (Lake George Association 2021). MaineDOT calibrates its spreaders annually each fall, or whenever any component of the system is repaired, replaced, or modified.

Sodium chloride (NaCl) remains the most commonly used and most cost-effective material for clearing roads. Melting occurs when the salt forms a brine. Sodium chloride loses effectiveness at temperatures below 15 degrees F, which leads to the use of additives that have similar effects but slightly different characteristics. The second most commonly used chemical (widely used in municipalities in Maine) is calcium chloride ($CaCl_2$), which is used to pre-wet salt or can be applied directly in anti-icing to prevent the bonding of ice to pavement. Magnesium chloride ($MgCl_2$) is also used to lower salt's melting temperature. It is often used as an additive to road salt or in anti-icing. Both calcium chloride and magnesium chloride are corrosive to metal, can increase slipperiness if used improperly, and are more expensive than sodium chloride. The choice of additives often varies due to fluctuating cost and manufacturing supply. Other materials available but not widely used include potassium chloride (KCl), urea, potassium acetate (KA), and calcium magnesium acetate (CMA). Nationally, efforts are ongoing to find more effective de-icing materials to replace chloride salts at reasonable cost. Promising research is being done on organic byproducts such as beet products, flower residue, cheese brine, and other locally available agro-wastes, but none yet perform at the scale and cost of chloride road salts (Shi 2019).

Impacts of Salt Use

Salt is carried from roads to surface waters by stormwater runoff or meltwater or can travel more slowly through contaminated groundwater. Chloride is completely soluble and very mobile in soil and water. There is no natural process by which chlorides are broken down, taken up, or removed from the environment. Only dilution can reduce their concentration. Most of the chloride applied to roads will end up in surface water or groundwater.

The economic impacts of the use of chlorides in Maine include the costs of deterioration of infrastructure and equipment, costs associated with salt storage, costs of materials applied, accidents, and costs associate with commerce and remediation (Tiwari and Rachlin 2018; Shi et al. 2014; Fay and Shi 2012). Social and public safety impacts result from crashes, groundwater and drinking water contamination, and loss of mobility on roadways. Environmental impacts result from road salts concentration in streams, wetlands, lakes, drinking water, soil, aquatic and semiaquatic life, roadside vegetation, and urban trees and plants. Our estimate of costs and impacts in this report does not encompass all of these.

Freshwater salinization has been noted worldwide, and it is estimated that between 37% of the drainage area of the U.S. has been affected by salinization over the past century (Kaushal et al. 2018). Trends of increasing chloride have been reported nationwide in streams as well as in glacial aquifers (Dugan et al. 2017; Kaushal et al. 2005; Mullaney, Lorenz, and Arnston 2009). While industrialization and land use are primary factors nationwide, salt for de-icing roadways is recognized as a major source of chloride to groundwater, streams and rivers, and lakes in northern North America and Europe (Dugan et al. 2017).

The environmental impacts from application of road salt manifest themselves more broadly, particularly in Northeastern and Midwestern states (Kelly, Findlay, and Weathers 2019). Rising chloride concentrations in U.S. surface waters in both urbanized and non-urbanized watersheds affect lake turnover and aquatic life. Chloride accumulations in groundwater impact drinking water and migrate through baseflow to surface waters. Road salt affects roadside vegetation through direct contact as well as by altering the chemical composition of soils (Tiwari and Rachlin 2018; Corsi et al. 2015).

The Maine Snow and Ice Control Best Practices Working Group concluded in 2015, "We now know there is an upward trend for salt concentrations in many northern freshwaters. Because there are no effective measures for removing dissolved salt from freshwater, it is critical to minimize the amount of salt used" (MSICBPWG et al. 2015).

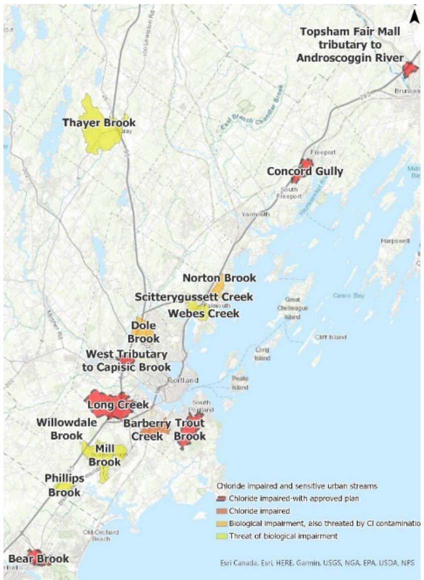
Surface Waters

Historic analysis of chloride levels in three major New England rivers shows that chloride increases correspond with the trend of New England population growth and industrialization from 1900–2000 (Robinson, Campbell, and Jaworski 2003). A USGS study of northern U.S. urban streams shows average chloride concentrations approximately doubling from 1990 to 2011, outpacing the rate of urbanization (Corsi et al. 2015). Chloride concentrations increased in all seasons but were highest during the winter. These findings suggest that chloride is stored in groundwater and slowly released over the year. Chloride levels in impaired waterbodies are often higher in times of lower water as there is not enough flow for dilution.

Chloride in surface waters can be toxic to some fish, insects, and amphibians. The impact of greatest concern is to freshwater organisms, and many scientists argue that regulations are needed to protect freshwater biodiversity (Cañedo-Argüelles et al. 2016). Chloride-contaminated water will settle to deeper parts of lakes or streams, impacting lake turnover and leading the lower layers of water to become oxygen deficient and unable to support aquatic life. Higher chloride in freshwater can kill zooplankton at the bottom of the food chain, altering aquatic life and potentially leading to algae blooms (Szklarek, Górecka, and Wojtal-Frankiewicz 2022). The EPA defines levels of chloride toxicity to fish and invertebrates: acute water quality criterion is 860 mg Cl/L; chronic water quality criterion is 230 mg Cl/L.

In Maine, the DEP started monitoring urban streams in the 1990s to restore and protect those that don't meet the standards. Twenty streams in Maine are now noted on the Maine DEP's list of chloride-impaired urban stream watersheds (MDEP 2019). Most of these are located in developed urban or suburban areas with significant amounts of impervious pavement or roadway. Chloride-impaired streams in southern Maine are shown in Figure 3.

Figure 3: Chloride-Impaired Urban Stream Watersheds in Southern Maine



Esri Canada, Esri, HERE, Garmin, USGS, NGA, EPA, USDA, NPS

Chloride can reach a stream either directly through runoff of stormwater or meltwater (acute) or by slowly infiltrating through contaminated groundwater (chronic) into the stream. In many of Maine's impaired streams, the chloride concentrations are highest during time of low flow, when groundwater supplies most of the stream flow. Non-winter storm events help dilute the chloride in the groundwater flowing into the stream. Streams most likely to have chloride impairments are those surrounded by commercial or dense residential land use, and many have interstate exchanges in the watershed (Maine DEP 2019b). When a stream is found to be impaired, a watershed management plan is developed and the DEP works with the municipality and local landowners to implement the plan to restore the stream. Whether a stream has an active management plan may depend on local leadership and participation. The salt-reduction practices may need to be stream specific, based on local conditions (Dennis 2021; Dennis and Feindel 2020). The impacts to watersheds are not limited to southern Maine. Figure 4 and Figure 5 show chloride-impaired watersheds in the Augusta and Bangor regions.

Figure 4: Chloride-Impaired Urban Stream Watersheds—Augusta Region

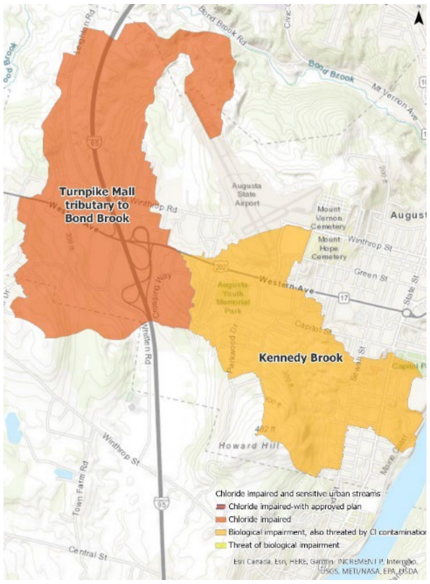


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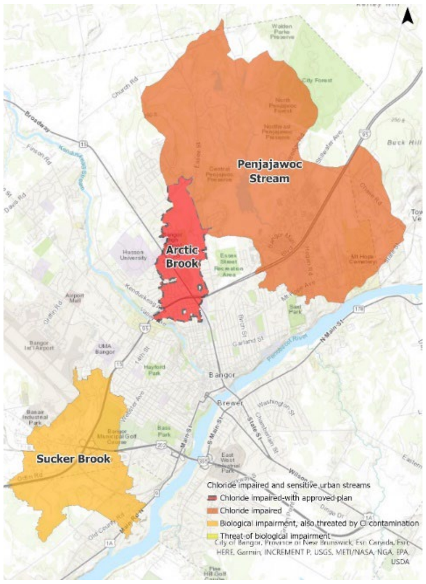
Figure 5: Chloride-Impaired Urban Stream Watersheds—Bangor Region



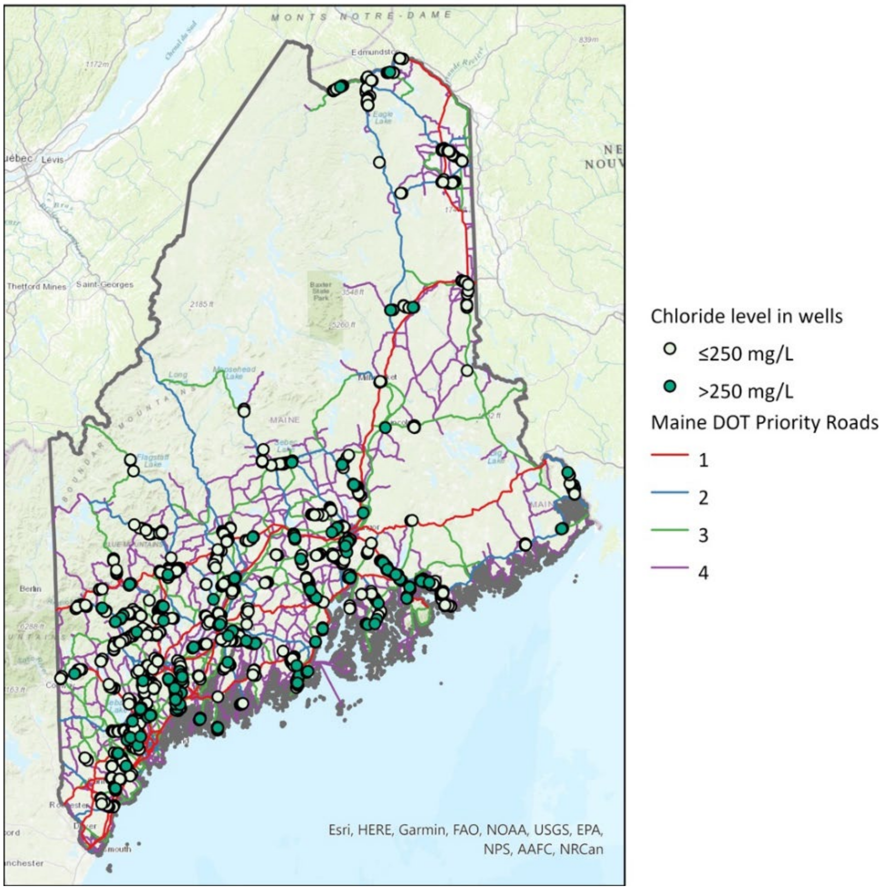
City of Bangor, Province of New Brunswick, Esri Canada, Esri, HERE, Garmin, INCREMENT P, USGS, METI/NASA, NGA, EPA, USDA

Groundwater

Freshwater is impacted by road salt primarily through infiltration, runoff to surface water, and through storm drains. The salt is transported by runoff, which recharges shallow groundwater and can then affect local rivers, streams, and lakes through groundwater baseflow (Brown et al. 2011). Given that flow levels are often lower in the summer and freshwater organisms are more active at that time, contaminated groundwater baseflow is of the greatest concern to vulnerable streams (Maine DEP 2019a).

Whereas in surface waters, salt can wash downstream, in groundwater, it resides much longer and can contaminate aquifers and wells that supply drinking water. Elevated sodium and chloride in drinking water supplies can cause human health impacts associated with high sodium intake, corrosivity causing plumbing failures and leaching of lead and copper into water systems, and the mobilization of manganese, iron, radium, and radon. Neither sodium nor chloride are listed chemicals for human health concerns, but the EPA has set standards for drinking water. The EPA Secondary Maximum Contaminant Level (SMCL) is based on taste and set at 250 mg/L of Na or Cl. The EPA advisory limit (associated with high blood pressure) is 20 mg Na/L.

Figure 6: Chloride Concentrations (mg/L) in Wells Sampled by the MaineDOT, 2001–2020



Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, AAFC, NRCan

A USGS study of wells in 19 states showed that the density of major roads was a factor in chloride concentrations in well water (Mullaney, Lorenz, and Arnston 2009). Most concentrations of chloride occur in shallow wells, wells that are near salt storage facilities, or wells downslope from heavily salted roads.

In Maine *public* water systems currently test for chloride and sodium. However, approximately 60% of drinking water in Maine comes from groundwater, and 40% of Maine households rely on well water. Figure 6 shows chloride concentrations (mg/L) in wells sampled by the MaineDOT. The groundwater well samplings were conducted from 2001 to 2020.

Long Creek Watershed: Pilot project for salt reduction

Long Creek is an urban stream in southern Maine with ongoing water quality impairments. The Long Creek watershed encompasses 3.5 square miles in a commercial and retail district located in four municipalities: Portland, Scarborough, South Portland, and Westbrook. It is an area of large impervious surfaces including parking lots and roads for retail and office development. Chloride is one of several pollutants found in Long Creek. Progress has been made on reducing some of these impairments, but chloride has remained difficult. Monitoring over the past 10 years shows that chloride levels remain high, with most of the monitoring sites exceeding EPA aquatic life thresholds.

The Long Creek Watershed Management District (LCWMD) was created in 2009 and is made up of private landowners, municipalities, two state entities, and a regional entity, and is managed by a board of directors. Their focus has been on reducing aquatic pollutants, and some progress has been made with other contaminants, but chloride levels in the stream remain elevated. Chloride in Long Creek comes from two major sources: public roads within the watershed and snow management on private property including private roads, parking lots, driveways, and walkways. The impervious cover receiving road salt application within the watershed is 15% municipal roads, 4% state roads, and 81% private roads and lots. The LCWMD study has found that the sources of chloride are 40% municipal roads, 4% interstate roads, and 56% parking areas (LCWMD 2015). A primary reason to reduce the chloride entering Long Creek is to reduce the chloride levels entering the groundwater during dry periods.

In 2020, the LCWMD hired a contractor to try a novel approach to chloride reduction. The program focuses on cost saving for landowners, providing an incentive for property owners who might not participate for solely environmental goals. This approach involves an accounting of all costs incurred by the property owner, such as environmental and infrastructure damage, based on metrics about the damage each ton of salt does to infrastructure in terms of money (e.g., deterioration of concrete; corrosion of rebar, aluminum door frames, and carpets). It also focuses on the watershed's goal of salt reduction and includes training for road salt applicators.

The pilot program is in its early stages. The consultant is first working with two private landowners and the city of South Portland. The first year is focused on information gathering and documenting current snow removal practices and how much salt is being used. GPS monitoring equipment is also used to track the movement of snow removal equipment, and measurements are taken from each truck so that each vehicle can be calibrated to a certain application rate. These measurements, alongside GPS tracking data, will show how much salt is being applied by the equipment.

Infrastructure and Vehicles

Salt used for winter road maintenance, though beneficial for public safety, has a well-documented impact on the infrastructure of concrete bridges, roads, and sidewalks, as well as corrosive effects on vehicles (Shi et al. 2009; Fay, Shi, and Huang 2013). Chloride can penetrate and deteriorate concrete on bridge decking and parking garage structures and damage reinforcing rods, compromising structural integrity. It can damage vehicle brake linings, frames, bumpers, and other areas of body corrosion. It impacts railroad crossing warning equipment and power line utilities by conducting electrical current leaks across the insulator that may lead to loss of current, shorting of transmission lines, and wooden pole fires. Repeated freeze and thaw expands and cracks the road surface.

Research suggests that the U.S. spends $5 billion a year to repair damages to road infrastructure from winter snow and ice control operations (Xu and Shi 2018). AAA estimates that road salt costs car owners nationally as much as $3 billion annually in repair costs for rust-related vehicle damage to brake lines, fuel tanks, exhaust systems, and other components (Edmonds 2017).

Current Winter Practices: Maine

The state of Maine's public roads are maintained in winter by MaineDOT, Maine Turnpike Authority, and municipalities and counties (MDOT 2017). With a population of 1.36 million, Maine reported approximately 1,649,049 registered motor vehicles and more than a million licensed drivers (Maine Bureau of Motor Vehicles 2020).[2] As a rural state, Maine has more miles of roadway per person than any other New England state, leading to a relatively high per resident cost for transportation maintenance and infrastructure.

Table 1: Maine Winter Miles by Jurisdictional Responsibility

Agent	Lane	Centerline	% of Total Lane Miles
MaineDOT	8,225	4,079	18
MTA	632	109	1.3
Municipal	36,729	18,283	80.6
State Total	45,586	22,471	

SOURCE: (MaineDOT, 2021)

The state's total winter mileage is roughly 45,585 lane miles. MaineDOT is responsible for maintaining 8,225 lane miles, equal to 4,079 highway centerline miles, consisting of interstate and state highway mileage. This is about 18% of the total roadway in the state. The Maine Turnpike Authority (MTA) maintains 632 lane miles (109 centerline miles) or 1.3% of the total roadway miles (Table 1). In addition to road mileage, MaineDOT is responsible for plowing in rest areas, park & ride lots, and MaineDOT facilities. They do not perform snow and ice control on sidewalks. The remaining 36,729 lane miles, representing 81% of Maine's total lane mileage, include state aid highways and municipal and county mileage and are maintained in winter by the 483 organized municipalities, 10 counties, and 3 reservations. Some unspecified amount of this mileage is contracted by municipalities to private contractors for winter maintenance. To examine the state as a whole we look at the operations, costs, and materials of the three groups responsible for winter road maintenance in Maine: MaineDOT, Maine Turnpike Authority, and municipalities. Each entity in Maine (MDOT, MTA, municipalities) makes its own determination for the level of service provided on its roads and for training. These and other practices are described in corresponding sections below.

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[2] Maine's population 1,362,359, 2020, US Census Bureau.

MaineDOT Winter Practices

In the mid-1990s, MaineDOT began adopting procedures recommended by the Federal Highway Administration for anti-icing. The adoption of salt-priority meant moving away from the use of sand on state roads. Currently, MaineDOT uses minimal amounts of sand. Reduction in use of sand corresponded to the adoption of anti-icing and lead to a reduction in overall material costs between 1999 and 2002.

MaineDOT currently uses an anti-icing policy on the majority of its roads, treating roads before ice and snow are able to bond to the roadway. This includes application of pre-wetted salt early in the storm to prevent ice bonding to the roadway. Without pre-wetting, up to 30% of the salt applied to roadways ends up bouncing or blowing off the road (MaineDOT 2021).The anti-icing policy does not include pre-treating roads with brine.

Pre-treating can provide an effective base to prevent the formation of ice on the pavement surface. In our 2009 report, we noted that an expanding piece of MDOT's anti-icing plan involved pre-treating roadways with liquid salt brine in selected priority areas. This practice relies on accurate localized weather information. In 2008, less than 15% of MaineDOT roads were pre-treated. Since then, MaineDOT has moved away from pre-treating, and current practices do not include pre-treating roads with brine. The state no longer owns the equipment to treat entire corridors. Salt applications occur with the plow trucks, using fully pre-wetted salt, usually at a rate of about 10 gallons per ton.

The decline in pre-treating with liquids on the part of MaineDOT has been gradual. Pre-treating can only be used under specific conditions on a subset of storms, and it requires special equipment for application of liquids. Those same funds are now used for standard trucks that can be used in every storm. Pre-treating requires additional infrastructure of brine makers and brine tanks. The general public does not well understand the effectiveness of pre-treating with brine, and this practice was a source of complaints from the public. Treating roads before the storm with liquids requires more labor, and with crews in short supply, MaineDOT chose to prioritize simple plowing (MaineDOT 2021). All MaineDOT drivers receive snow and ice training, which typically consists of WISE College early in their career (essentially, awareness training), then Snowfighter training, which is more hands-on. Snowfighter training leads to a person becoming "Snowfighter certified."

Level of service

Levels of service are defined by MaineDOT according to this chart, which corresponds to highway corridors noted in the map below. Interstate mileage is cleared first, with priority decreasing to smaller, slow-speed roads.

Table 2: MaineDOT Level-of-Service Goals

Roadway Type & Priority	MaineDOT Level of Service Goals	Route Length in Centerline Miles
P1 Interstate	South of Exit 197 both travel and passing lanes and north of Exit 197 the travel lane will normally be clear within 3 daylight hours after a storm. Maximum recommended travel speeds during a storm will normally be 45 mph but may be less during extraordinary events.	10
P1 Non-Interstate	Travel lanes will normally be clear within 3 daylight hours after a storm. Maximum recommended travel speeds during a storm will normally be 40 mph but may be less during extraordinary events.	10
P2	Travel lanes will normally be clear within 8 daylight hours after a storm. Maximum recommended travel speeds during a storm will normally be 35-40 mph but may be less during extraordinary events.	12
P3	Travel lanes will normally be clear within 24 hours after a storm. Maximum recommended travel speeds during a storm will normally be 35-40 mph but may be less during extraordinary events.	14
P4 and P5	Travel lanes will normally be clear within 30 hours after a storm. Maximum recommended travel speeds during a storm will normally be 35 mph but may be less during extraordinary events.	16

Source: MaineDOT, 2020

Figure 7: MaineDOT Highway Corridor Priorities

Maine Turnpike Authority Winter Practices

The MTA mileage includes 23 interchanges, 5 service plazas, and the Kittery Rest Area from the state line in Kittery to the end of the Turnpike in Augusta. Like MaineDOT, MTA moved away from the use of sand and towards anti-icing in the 1990s. Currently they employ 77 plow trucks to support winter maintenance on its 632 lane miles of highway with the goal of making the Turnpike passable during a storm and all areas of the Turnpike free of snow and ice as soon as possible after the storm.

The MTA's anti-icing strategy involves treating the roadway early during the onset of weather events to prevent snow and ice from bonding with the pavement. The MTA pre-wets solid material as it is being applied to the roadway to activate the salt and prevent bounce and scatter of the material (MTA 2020). In our 2009 report we noted that MTA had a policy of pre-treating with brine since 2006; like MaineDOT, however, MTA does not pre-treat the roadway with salt brine at this time.

The MTA uses Roadway Weather Information Systems (RWIS) to collect weather information including pavement temperatures. Some are predictive weather stations that help maintenance crews to determine when the road will freeze, allowing MTA to take a more proactive approach to treating the road during icing events.

Level of service

The Maine Turnpike Authority has a bare pavement policy, stating that all areas should be free of snow and ice as soon as possible. During heavy storms when it is not possible to remove snow and ice simultaneously from the roadway, shoulders, parking areas, crossovers, etc., the following priorities are adhered to unless otherwise directed (MTA 2022).

Table 3: Maine Turnpike Authority Road Priority

Level	Description
First Priority	Mainline pavement, toll plazas, interchanges, service area ramps, and median crossovers
Second Priority	Shoulders, toll facility parking lots, service area parking lots, and access roads
Third Priority	Other facilities and parking lots
Fourth Priority	Final cleanup and snow removal at service areas, parking areas, gores, and bridges

Municipal and County Winter Practices Survey

Maine has 483 towns and cities, 3 reservations, and 10 counties with responsibility for winter road maintenance. These municipal entities are responsible for 18,283 centerline miles of road, or approximately 80% of the state total roadway. Municipal governments either provide winter maintenance services directly through a public works department or town employees, or use private contractors.

Municipal maintenance varies from state-level winter road maintenance in some significant ways. Road surfaces, traffic patterns, and volume are different from state highways, while training, equipment, and technology are more varied. There is no uniform set of conditions for municipal roads; climate, slope, elevations, and volume all influence local conditions. Municipalities differ from each other in budget keeping, population density, and levels of service. Some of Maine's cities provide higher levels of service in downtown areas, clearing sidewalks, parking lots, and schools. With the assistance of MaineDOT, we surveyed nearly 500 units of local government including municipalities, counties, tribal governments, and plantations on their winter practices for the winter of 2019–2020. This report's information on municipal practices, materials, and costs comes from that survey. See Appendix 1 for details on the survey. The survey was sent by email from MaineDOT's Maine Local Roads Center to municipalities in the state with a link to an online survey and an attached version of the paper survey. We received 246 responses. Respondents range from Maine's largest cities to towns with population of fewer than 100 residents.

Survey response rate and weighting

The 246 municipalities that responded to the survey represents about 51% of Maine's total. The responding municipalities constitute about 65% of Maine's total population of 1.34 million. To extrapolate the winter maintenance costs and practices for the entire state, we scale or weight the observations in our sample. All municipalities across the state were placed into bins based on their DOT region, population, and number of winter lane maintenance miles. There are 125 different bins representing combinations of DOT region, population, and lane mile categories. We examined the frequency of responses in each bin (for example, the number of municipalities that[3] exist in *DOT region* 1, *population category* 3 and *lane mile category* 4) compared to the state as a whole. Responding municipalities were then assigned a weight such that our survey sample is reflective of the state as a whole.[4] Additionally, for total winter maintenance costs and total salt and sand purchases, we took into account *question-level* missing data (non-responses). If a responding municipality did not answer a particular question, we assigned them the *average value* for their bin, using the same categories as the weighting factor described earlier. Finally, though we asked municipalities to report their total centerline winter maintenance miles, not all answered. Instead, we used data provided by MaineDOT on municipal winter-maintained miles by municipality.

Reponses by municipal size and region

As seen in Figure 8, a higher proportion of municipalities with larger populations completed the survey, though overall we got more responses from small municipalities due to their larger proportion in the state. We did get responses across all size classes.

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[3] For example, if a survey respondent within DOT region 1, population group 2, lane mile group 3 did not answer the total cost question, we assigned them a total cost equal to the average cost reported by all of those communities who fall in the same bin.

[4] By "state as a whole," we mean all municipalities that have winter road maintenance miles; our scaling does not take into account communities that either do not have any winter road maintenance miles or are unorganized and thus have decisions made at a county level.

Figure 8: Responding Municipalities by Population Size

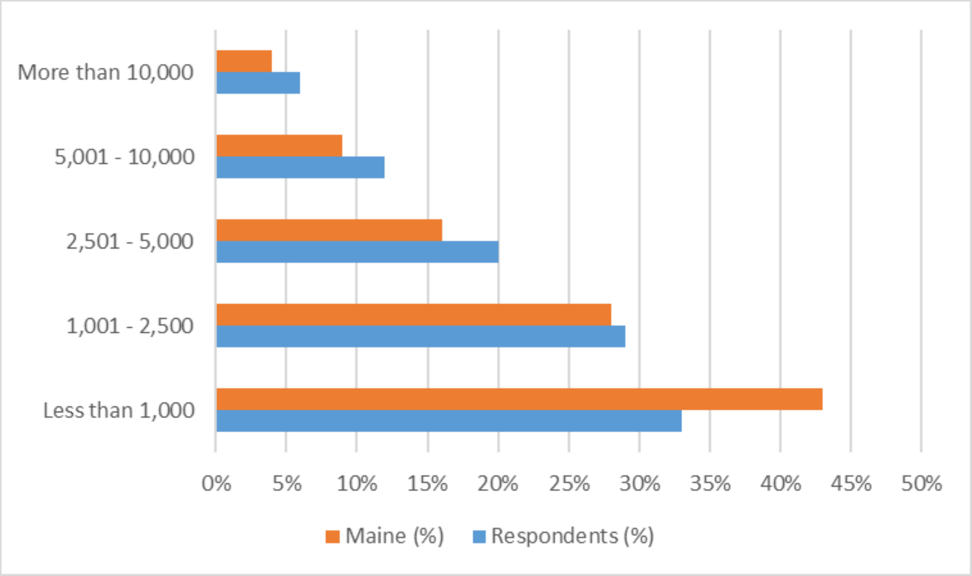


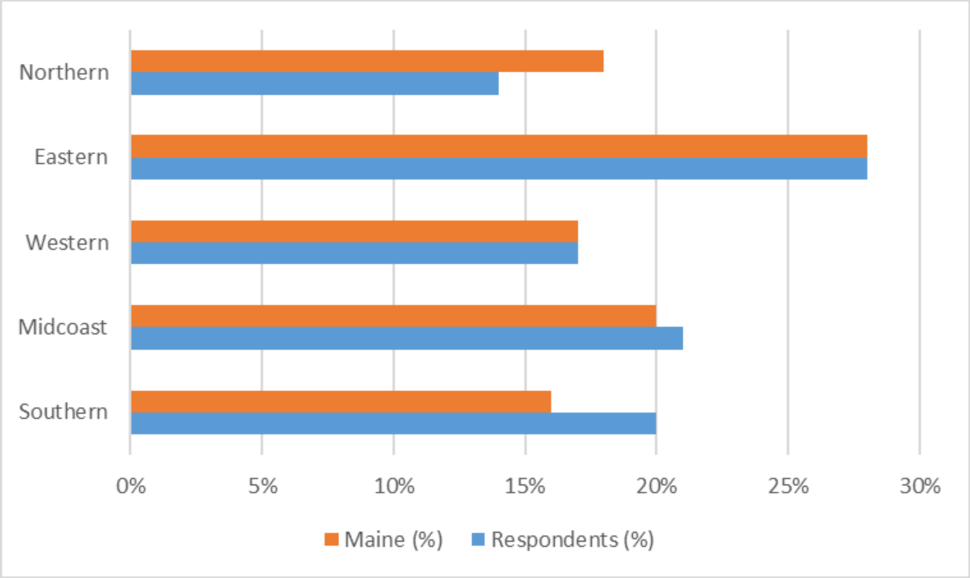
Table 4: Maine Municipal Winter Miles

MaineDOT Region	Centerline Miles	Lane Miles
1	5,722.41	11,562.06
2	4,010.54	8,030.96
3	2,840.90	5,686.36
4	3,772.93	7,566.96
5	1,935.80	3,882.62
State Total	18,282.58	36,728.96

Source: MaineDOT, August 2021

MaineDOT designates five zones across the state (Northern, Eastern, Western, Midcoast, Southern). Our survey responses from the Southern and Midcoast regions are higher than proportional compared to the Northern region where there are fewer than proportional, Figure 9.

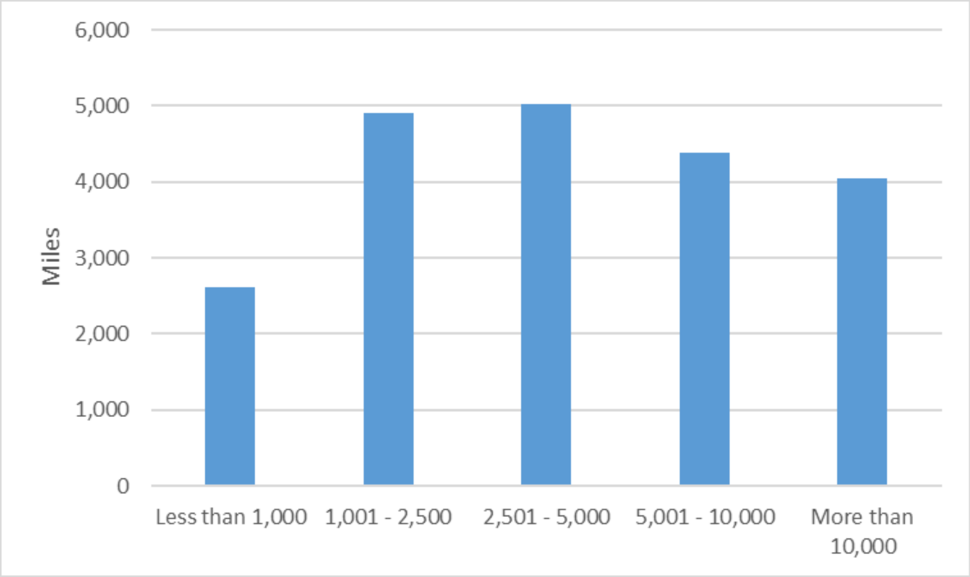
Figure 9: Maine Municipalities by DOT Region



Winter maintenance responsibility

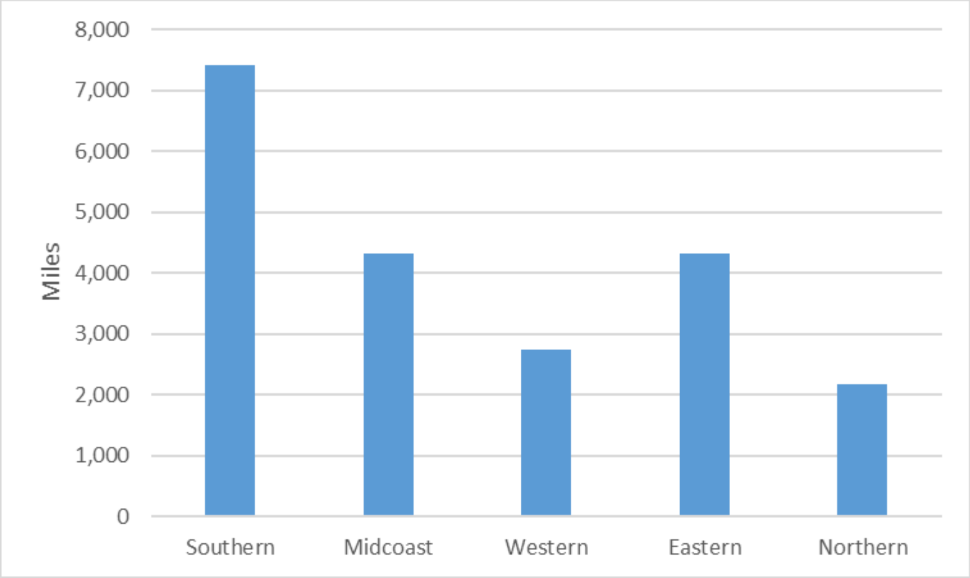
The municipalities that responded to this survey are responsible for a total of 20,960 winter lane miles, *approximately* 57% of the winter lane miles maintained by all municipalities statewide. Given their greater number, the responding small and mid-sized municipalities maintain the most lane miles, Figure 10.

Figure 10: Respondent Winter Maintenance Lane Miles by Population Size



The survey responses from the Southern, Midcoast, and Eastern regions make up a greater proportion of the statewide lane miles than the Western and Northern responses, Figure 11.

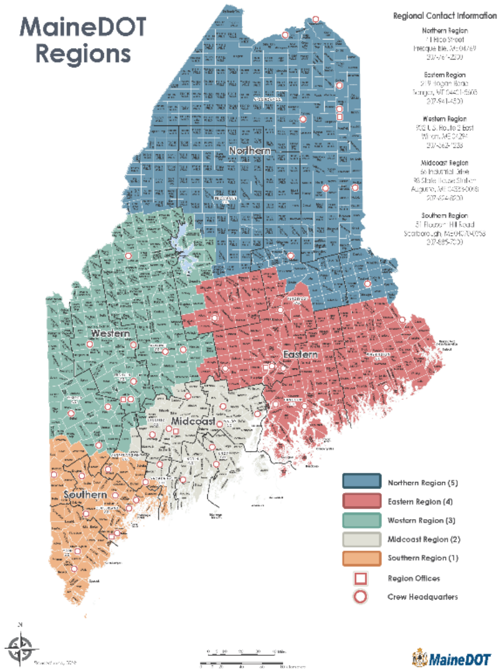
Figure 11: Respondent Winter Maintenance Lanes Miles by Region



Municipal survey results: Practices

Our 2020 survey of Maine municipalities reveals details on municipal operations, the results of which are also examined by the five geographical regions used by MaineDOT and by population size (see Appendix 1 for details).

Figure 12: Map of DOT Regions Used to Compare Results of Municipal Survey



Among municipalities surveyed, 28% report using an anti-icing maintenance strategy. Some 72% of responding towns reported relying on application of “sand with some salt in it” rather than “anti-icing.” Communities in the Northern region are more likely to use traditional method of “sand-with-salt" (94% of responding use that approach). The Southern region has the highest rate of anti-icing (53% of southern municipalities surveyed). Communities with a population below 5,000 were more likely to rely on sand, while higher-population communities were more likely to use anti-icing. More contracted crews than municipal crews rely on sand, likely reflecting that smaller towns contract out their maintenance more frequently than larger cities. Also, 12% of responding towns reported pre-treating their roads. (We did not ask whether pre-treating involved liquids or pre-wetted salt.) Not surprisingly, towns larger than 5,000 have the highest rate of pre-treating, while smaller towns have the lowest. Communities in the Western region are more likely to pre-treat (35% of western municipalities surveyed). The Eastern region is least likely to pre-treat (4% of eastern municipalities surveyed). More municipal crews than contracted crews report pre-treating. In our survey 29% of Maine municipalities report pre-wetting their salt always or sometimes, suggesting that there is room to improve effectiveness at the municipal level.

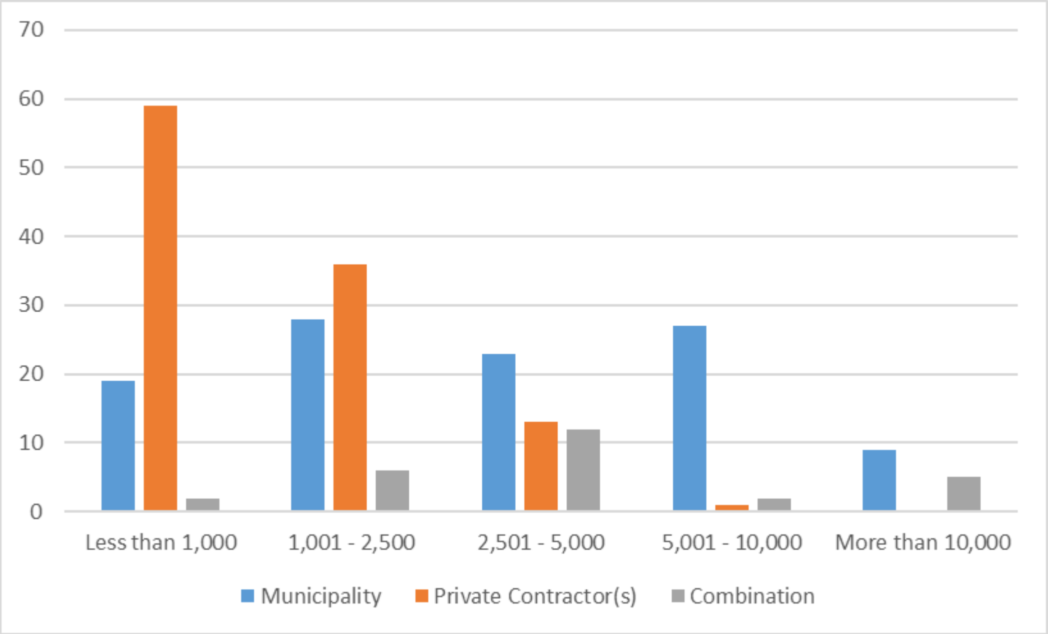
Most of responding towns (71%) also include sidewalks and parking lots in their operations. Those specifying this mileage reported maintaining a total of 1,165 sidewalk miles and 13 million square feet of parking lots.

Statewide, 71% of towns surveyed report that they never pre-wet their salt before spreading, while 12% report that they always do. Communities in the Southern region are more likely to "always" pre-wet (22% of respondents) than the other regions. Larger municipalities are more likely to pre-wet; 100% of respondents from towns larger than 10,000 report that they “always or sometimes” pre-wet their salt, while 58% of towns with population between 5000 and 10,000 do so.

Calibration of equipment is recommended practice to avoid over-salting. MaineDOT employs this practice, and MaineDOT’s Maine Local Roads Center training program teaches calibration techniques to municipalities. Recent experience from New York DOT and municipalities recommends monthly calibration of equipment (Lake George Association 2021). We do not have specific detail on the frequency of calibration in Maine municipalities.

Responding towns reported a relatively even split between those who use municipal crews (106) and those who use private contractors (108). A few (27) reported using a combination. Municipalities with smaller populations were more likely to use contractors for their winter maintenance.

Figure 13: Winter Maintenance Crew Type by Municipal Size



These findings on municipal operations type are consistent with the rural composition of Maine as small towns with limited budgets, equipment, and staff make up the majority of the road mileage maintenance in the state. Larger communities have more flexibility in their budgets, ability to replace equipment, and staff to implement new practices.

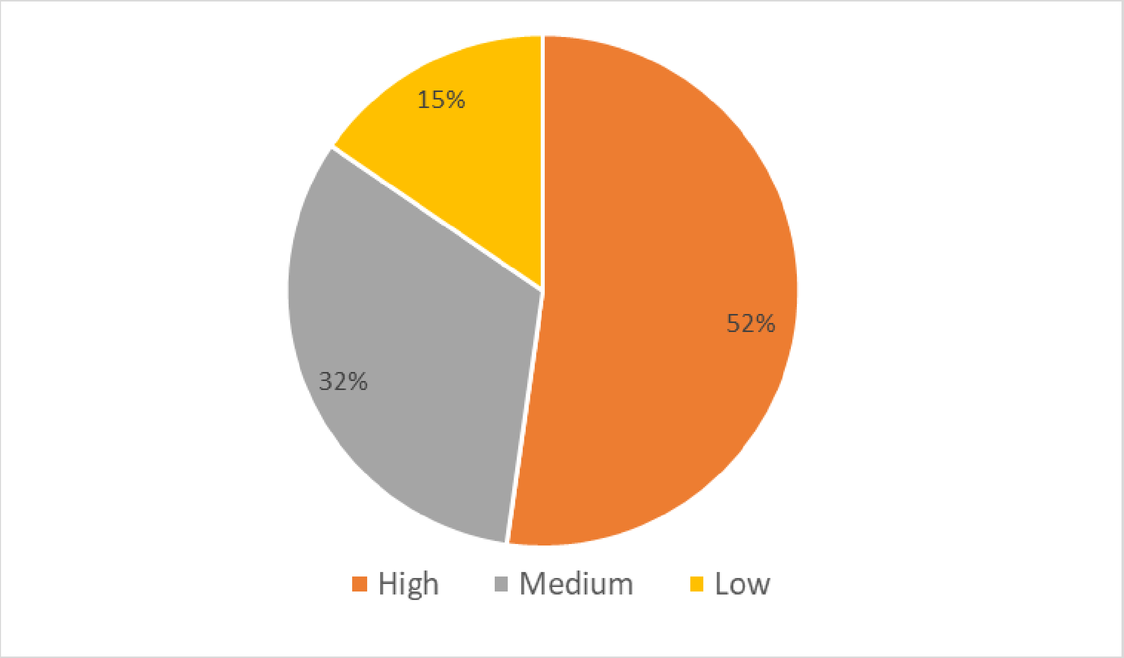
Of municipalities that responded to our question on training (N = 189), 69% reported that their drivers receive training. Municipal crews were more likely (89%) to receive training than contracted crews (45%). We also asked about whether towns follow the guidance of “Maine BMP for Winter Road Maintenance” noted earlier in this report. While 65% of responding towns report having seen the document, only 36% report using it in their operations.

Among responding towns, 9% report some municipal areas that require special practices for winter maintenance, such as wetlands or public water supply, and 19% reported that they have had a well claim for salt contamination in their jurisdiction at some time in the past.

Level of service

Survey respondents self-identified their level of service by priority ranking of high, medium, and low. Figure 14 shows the miles-weighted level of service reported. Collectively, just under 52% of municipalities' roads are considered high priority, while 32% and 15% are considered medium and low, respectively. A majority (70%) of the responding towns reported, however, that they have not formally defined and communicated a policy on level of service for their roads.

Figure 14: Municipal Respondent Winter Lane Miles by Priority



Winter Materials

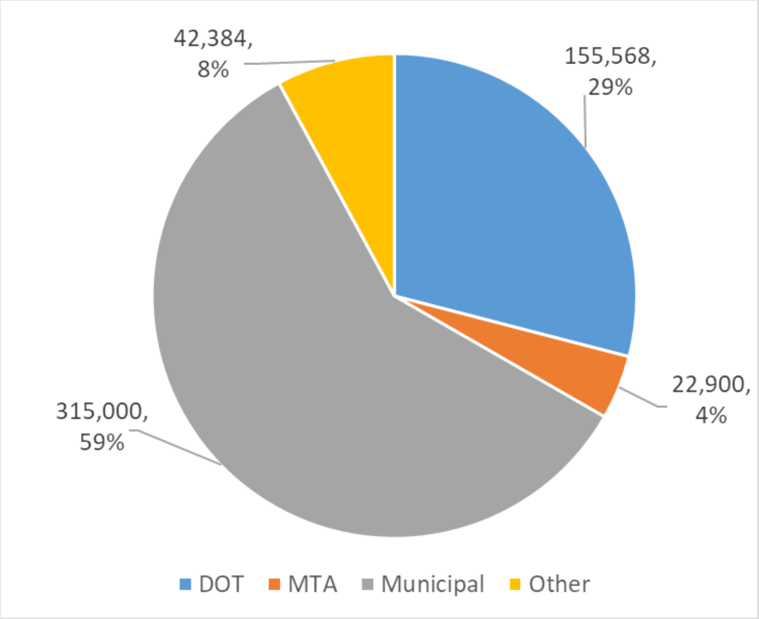
Prior to 2006, it was standard to treat roads with a salt and sand mix. Sand was widely discontinued on state roads for environmental and cost reasons. It continues to be used on many municipal roads. The introduction of anti-icing (pre-treating roads with brine and pre-wetted salt) meant less sand was applied to roads, reducing crashes and costs while improving overall safety. Salt use, however, continues to increase both in Maine and nationwide.

Statewide salt supply

To determine the total amount of road salt used in the state of Maine as a whole, we must consider state use, municipal use, commercial use, and private residential use. We gathered this information in two complementary ways: (1) asking bulk salt distributors how much they sell in Maine, and (2) asking MDOT, MTA, and municipal governments how much they use. For bulk supplies, we consulted the five commercial suppliers of road salt to the state by phone and email and asked how much they had sold to all entities within Maine during the 2019–2020 season. The companies consulted were Eastern Salt Company, Harcros Chemicals, New England Salt Company, Maine Salt Company, and Morton Salt. Collectively, they report 535,852 tons (1,071,704,400 pounds) of bulk and 854 tons of bagged salt for the winter of 2019–2020. This encompasses the bulk salt market and *some* portion of the bagged salt market. The bagged salt likely does not include the full amount of bagged salt used by homeowners or contractors. This compares with our estimate of 493,498 tons from our asking our large end-users MDOT, MTA, and municipal governments on how much they purchased. The difference shows 42 tons, 9%, more according to bulk distributors than noted by our large end-users. We note the relatively close agreement in salt use given these two different ways of collecting this data. The 9% greater amount reported by bulk distributors is likely explained by the non-road use of salt on commercial and industrial parking lots and other private uses.

This bulk amount represents 787 pounds per person for every Maine resident, or about 12 tons per lane mile in the state. The figure below illustrates how that total amount is distributed among the primary users of road salt.

Figure 15: State Salt Use Total (Tons), 2019-20



The actual amount used in any one year is a combination of stockpiles left from prior years and the current year's use, while a remainder may again carry over. Estimating that municipalities tend to know their needs and these average over more than one year, we use the figure of what was purchased in a year as representative. Private use is made up of homeowners, private roads and parking lots, airports, colleges, shopping centers, and businesses. We did not calculate statewide estimates for sand or for other winter road chemicals.

MaineDOT materials

The materials currently used by MaineDOT are salt, salt brine, and a liquid de-icer called Magic Minus Zero®, a patented blend of magnesium chloride ($MgCl_2$) and molasses, which is effective at de-icing lower temperatures than road salt (below -35F). Magic Minus Zero® also claims to be less corrosive to concrete and metals and safer for vegetation. It can be used directly on pavement for anti-icing or mixed with solid salt for pre-wetting (Nature's Mulch 2021).

Table 5: MaineDOT Winter Road Materials and Costs, 2019-2020

Materials	**Cost**
Salt	155,568 tons
Sand	3831 yd^3.
Magic Minus Zero (*)	283,687 gallons
Brine applied	364,821 gallons
Liquid Blend	299,254 gallons
Average salt price	$63 per ton
Total material cost	$12,097,049
Total snow and ice expenditure	$46,167,855
Total snow and ice expenditure – 5 year average	$39,736,975
MDOT Lane miles maintained	8225
Cost per lane mile	$5642

Source: Personal Communication MDOT, *MMZ is a Magic-0 is a proprietary blend of magnesium chloride and feed grade molasses used for anti-icing

To put these costs into perspective, Table 6 shows winter maintenance costs by other New England States.

Table 6: MaineDOT's Salt Use Compares with Other Northeastern States

State DOT	Salt use, 5-yr. avg.	Tons per lane mile
New York	1,004,973	22.95
Vermont	143,407	22
New Hampshire	204,817	21.88
Maine	146,777	17.74
Connecticut	156,059	14.36

source: ClearRoads, 2021

MTA materials and costs

For the winter of 2019–2020, the MTA used 22,900.1 tons of salt, 118,544.4 gallons of brine (in pre-wetting), and 6,405.2 gallons of $MgCl_2$. MTA does currently have stockpiles of salted sand that it would use if road and environmental conditions dictated. Last season they used no salted sand.

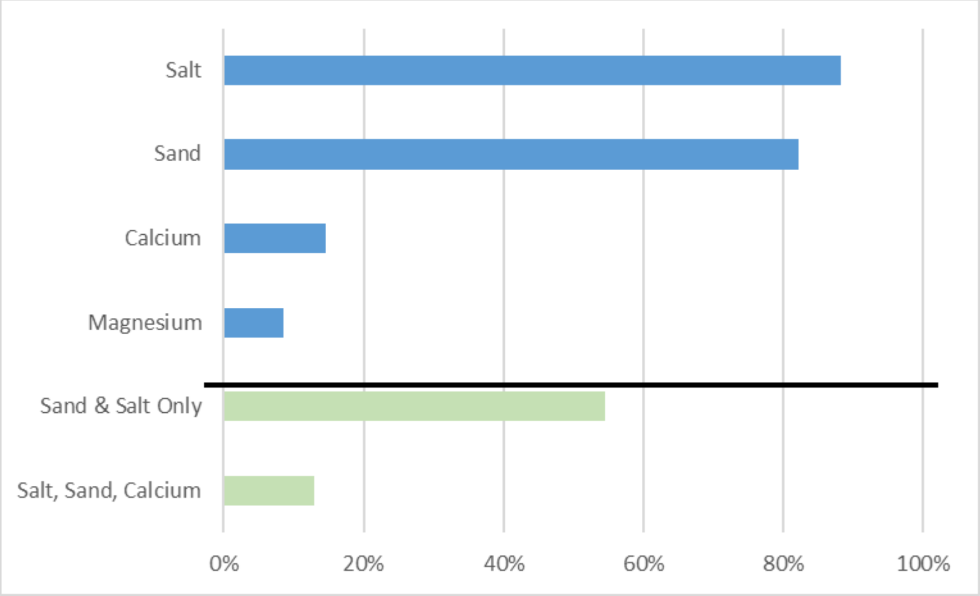
Table 7: Maine Turnpike Authority Material Use, Winter 2019-20

Materials used	Quantity	Costs
Salt (tons)	22,900	$1,276,904
Brine (gallons)	118,544	$29,636
Magnesium Chloride (gallons)	6,405	$9,351
Total Materials		$1,315,891
Source: (Taddeo 2022)		

Municipal materials

By far the greatest material used by Maine municipalities is road salt (NaCl) with almost 90% of municipalities reporting purchases. Most municipalities, 82%, also report purchasing sand, and a lower number report the use of calcium chloride and magnesium chloride, see Figure 16.

Figure 16: Material Use Reported by Municipal Governments



The total amount of salt purchased by our respondents reported (N=217) equals 187,000 tons in the 2019–2020 season. Extrapolating to the entire state, we estimate that all municipalities purchased 315,000 tons of salt during this season. We estimated the distribution of salt purchased by geographic region, based on respondents to the survey. We estimate that municipalities the Southern region purchased 138,000 tons of salt, a majority of the entire salt purchased across the state. This is consistent with weather patterns of freeze/thaw and freezing rain being more prevalent in the south.

Table 8: Salt Purchased by Municipalities in 2019-2020 across MaineDOT Regions

Region (weighted)	Total Tons
Southern	138,332
Midcoast	58,862
Western	35,982
Eastern	64,906
Northern	16,948
Total	315,030

Many small municipalities rely on use of sand. Municipalities responding to our survey purchased 502,000 cubic yards of sand. Extrapolating to the entire state, 894,000 cubic yards of sand were purchased during the 2019–2020 winter season. We estimate that the Northern region purchased the least amount of sand and the Eastern region purchased the most. We are unsure why they Northern region purchased the least amount of sand, perhaps this reflects unused stockpiles from the previous year or other factors.

Table 9: Sand Purchased by Municipalities in 2019–2020 across MaineDOT Regions

Region (weighted)	**Total Cubic Yards**	**Average Cubic Yards**
Southern	167,016	3,977
Midcoast	200,531	4,775
Western	179,056	5,426
Eastern	248,342	4,435
Northern	98,771	3,405

De-icers such as calcium chloride ($CaCl_2$) and magnesium chloride ($MgCl_2$) have a lower effective temperature than sodium chloride and can be mixed with salt to facilitate melting at lower temperatures. Fewer than half the survey respondents reported using additional de-icers. Some towns use more than one type of additional de-icer. The most common other de-icer selected was calcium chloride.

Table 10: Use of Other De-icers by Municipalities 2019-20

De-icer (Responses not weighted, N = 155)	Use	Percentage
Calcium chloride (CaCl2)	36	23%
Magnesium chloride (MgCl2)	21	14%
Other	17	11%
None	81	52%

Respondents reported their total purchases of $CaCl_2$ (66,000 gallons and 3,000 tons) and $MgCl_2$ (103,000 gallons and 10,000 tons). Given the small number of towns (52) reporting use of these additional de-icers, we do not weight these figures statewide.

Table 11: Amount Other De-icers Purchased by Municipalities

$CaCl_2$ (Gallons)	$CaCl_2$ (Tons)	$MgCl_2$ (Gallons)	$MgCl_2$ (Tons)
Responses unweighted, N = 52			
65,970	3,149	104,377	10,405

What is notable about the mix of materials at the municipal level is how it differs from state agencies. A much greater proportion of sand use by municipalities contrasts with the change made by MaineDOT and MTA to anti-icing policies. Most towns, especially smaller ones, continue to rely on sand. This practice is common in smaller municipalities across the Northeast.

Winter Maintenance Costs: Statewide

The total costs to MDOT, MTA, and Maine municipalities for winter road maintenance in the winter 2019–2020 season is $155 million. The breakdown of these expenses are given in Table 12. Components of these costs are described by jurisdiction.

Table 12: Winter Maintenance Expenditures Total: MDOT, MTA, Municipal

Entity	Total	Cost/Lane Mile
MDOT	$46,167,855	$5,613
MTA	$4,219,892	$6,677
Municipal	$104,452,531	$2,844
Total	$154,840,278	$3,397

As is seen, the municipal governments are responsible for 67% of all statewide expenditures on winter road maintenance including materials equipment and labor. This reflects the fact that municipal governments are responsible for 80% of all lane miles. Both MDOT and MTA have higher overall costs per lane mile than municipal governments, also reflecting that these state roads are maintained at an overall higher level of service.

MaineDOT costs

Nationwide, Maine typically ranks in the top five states in cost per lane mile for DOTs, and for the winter of 2019–2020, MaineDOT ranked highest in cost per lane mile in the country. New England states are consistently the highest cost because of weather; others in the top 5 are typically VT, NH, MA, NY. Costs may depend on materials used, level of service, labor rates, equipment, and weather patterns.

Maine ranks 7th in the nation in percentage of public miles that are state responsibility (USDOT FHWA 2014). MaineDOT's snow and ice budget usually ranges from $42 to $46 million and is based on 30–40 storms per year. MaineDOT's winter maintenance costs for 2019–2020 totaled $46.17 million.

Table 13: Winter Expenditures: MaineDOT

Year	Costs
FY 2016	$29,637,078
FY 2017	$37,832,863
FY 2018	$44,407,623
FY 2019	$46,397,520
FY 2020	$46,167,855
Source: MaineDOT	

Table 14: Breakdown of FY2020 Winter Expenditures MaineDOT

Expenditures
$19.11 million for salaries and benefits
$10.5 million for salt purchases
$450,000 for MgCl2 and CaCl2
$1.2 million for Other Highway Materials[5]
$10.5 million for equipment
Source: MaineDOT

MTA costs

Costs for the winter of 2019–2020 for MTA are a combination of material, labor, and equipment costs. Equipment costs were derived from vehicle maintenance costs incurred during the months of November through March, including truck parts, outside services, fuel, and vehicle maintenance staff costs. Together these total $4,219,892.

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[5] Other expenditures are mostly plow blades.

Table 15: Breakdown of FY2020 Winter Expenditures MTA

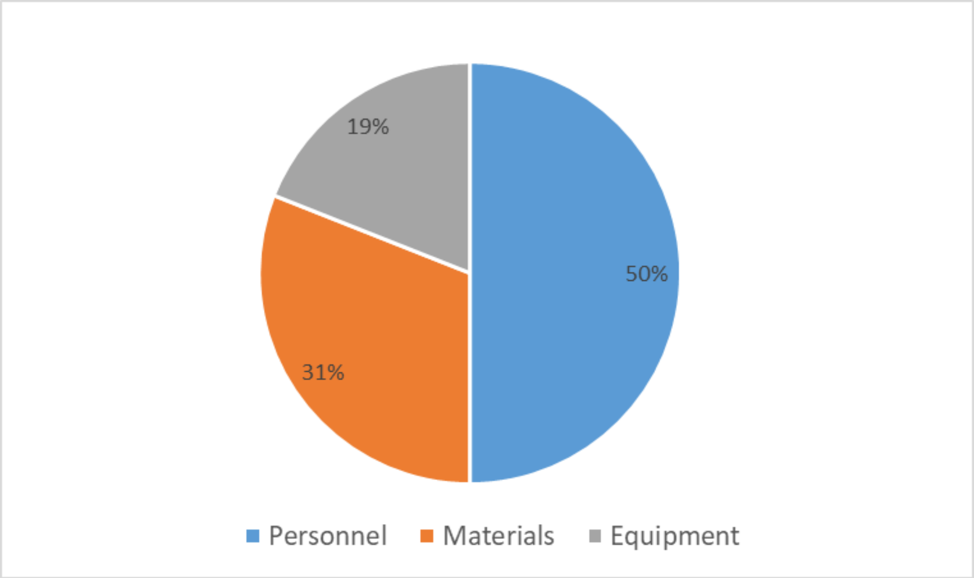
MTA Winter Budget 2019–20	**Costs**
Total Materials (Salt, Brine, $MgCl_2$)	$1,315,891
Winter Maintenance Labor Costs	$1,504,001
Winter Maintenance Equipment Costs	$1,400,000

Source: MTA

Municipal costs

At the municipal level, winter road maintenance is a significant portion of a local budget. Responding municipalities report having a total winter maintenance budget of $54 million during the 2019–2020 winter season. This figure includes personnel (50%), materials (31%), and equipment (19%). Communities spent, *on average*, $256,000, with some spending as little as $3,830 and others spending as much as $2,300,000. When *extrapolating* to the state as a whole (based on DOT region, population, winter lane miles maintained), we estimate that all municipalities spent an estimated $104 million on winter road maintenance during the 2019–2020 season.

Figure 17: Respondent Municipal Winter Budget Breakdown:



Municipalities were asked categorize their expenses by estimating what percentage of their total cost was spent on personnel, materials, and equipment, and in some cases, contractors. We see in Figure 17 that for municipalities that do some or all of their winter maintenance activities about 50% of their expenditures are for labor, 30% is for materials (primarily salt), and 20% for equipment.

Figure 18: Respondent Winter Road Maintenance Cost by MaineDOT Region

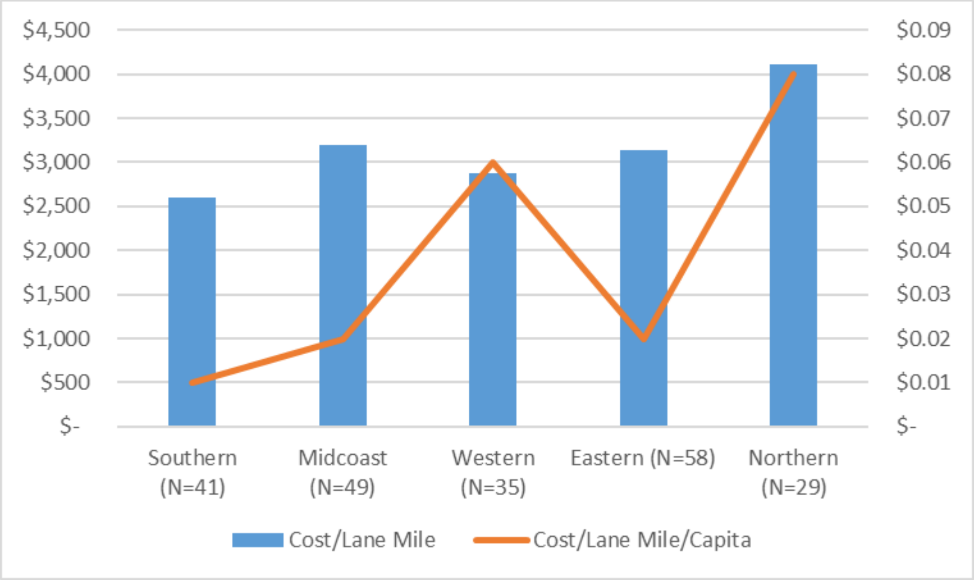
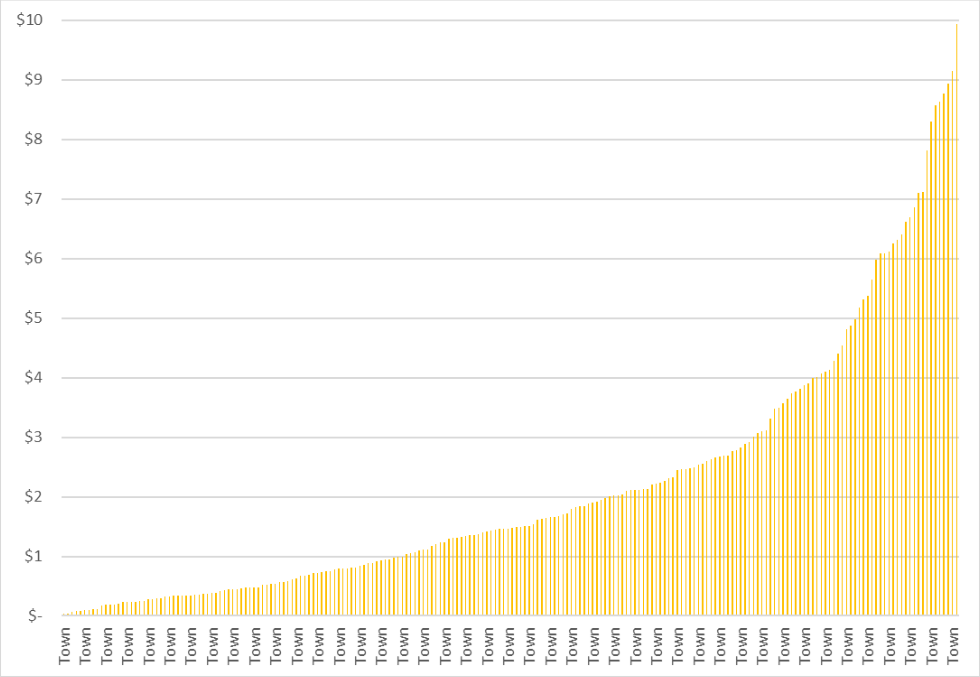


Figure 18 through Figure 20 shows costs per lane mile reported in the survey as well as the corresponding per capita costs. The costs per lane mile vary widely across municipalities. These, of course, reflect the differing geographies and weather experienced around the state as well as size of the municipality and number of miles of roads and sidewalks maintained. These cost differences also reflect different choices on the level of service and how it is provided (municipal workers or contractors). On average municipalities in the Northern and Western regions report much higher costs per lane mile when viewed per capita, with an 8-fold difference in costs, which is likely due to the higher winter severity that is routinely experienced in this part of the state and the lower population density.

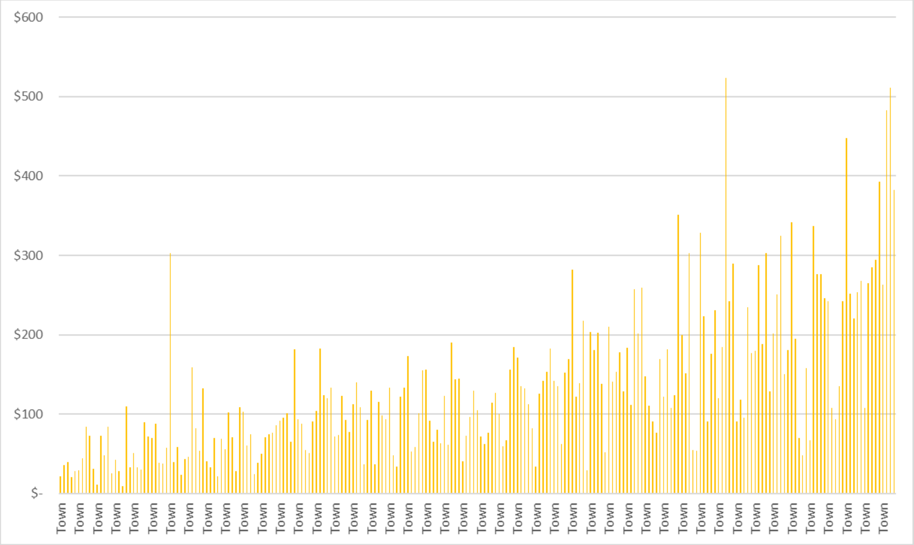
As is seen in Figure 19, there is a large range in winter maintenance costs by lane mile. We have truncated the full range of costs at $10 per lane mile, which eliminates displaying about 20 municipalities with *very large* per lane mile costs because they skew the figure and compress the variation among most of the respondents.

Figure 19: Total Costs per Lane Mile



The variation in costs between municipalities are not only due to their size in terms of population. Figure 20 shows the total costs of winter maintenance reported by towns with a populations greater than 100 people.

Figure 20: Winter Maintenance Costs per Capita by Municipality Size > 100 People



The number of miles and population size strongly affects the costs of municipal winter maintenance costs. Many municipalities have costs per lane mile per capita at about $0.01 year, but many do not. Some of this cost variation may also be explained by municipal-level decisions to clear sidewalks. Nonetheless, there remains significant variation in costs. This suggests there is likely room for changes in maintenance practices to reduce winter road maintenance costs. Unfortunately, we do not have any objective measure of the quality of winter maintenance efforts or the speed and thoroughness of activities by which to rank outcomes that may also help explain costs differences.

Well Contamination in Maine

Road salt, usually sodium chloride, is 40% sodium and 60% chloride with up to 5% of trace elements or possible contaminants (Tiwari and Rachlin 2018).[6] While sodium ions tend to bind to soil particles, the chloride ions can be temporarily retained in the soil before gradually discharging to groundwater (Kincaid and Findlay 2009). With time, the chloride ions move with water seeping through soil, joining streams and accumulating in aquatic sources (PMRA 2006). Groundwater sources thus can act as both a source and sink for chloride ions, accumulating the chlorides over time and discharging them to streams during dry periods. Besides winter road salt application and its storage, industrial waste, fertilizers, water softeners, sewage, and saltwater intrusion can influence sodium and chloride concentrations in groundwater (CDPH 2018). Fay and Shi (2012) note that shallow wells are more susceptible to contamination by road salts. Furthermore, "wells most likely to be affected are generally within 100 ft. (30 m) down-gradient of the roadway in the direction of groundwater movement" (Fay and Shi 2012). Local biophysical factors such as the soil ion exchange capacity, hydraulic conductivity, and location of water table play mediatory roles in the transport of road salt to groundwater reservoirs (Ramakrishna and Viraraghavan 2005). As such, the prevalence of chloride contamination in wells across Maine cannot be directly inferred from spatial patterns of road salt application, as it results from the interplay between natural and human factors, such as local hydrogeology, climate, land use, to name a few. In Maine, more than half of all homes rely on private wells for drinking water (Maine CDC 2021), and understanding the emerging patterns of well contamination is a first step to delineate chloride risk zones and make informed decisions regarding winter road salt application.

Well Contamination Data

The Maine Well Database maintained by Maine Geological Survey (MGS) records information for domestic well drills in Maine. The dataset is based on the mandatory reporting program, which requires drillers to submit well information. There are 76,869 records, and the drilling period ranges from 1990 to 2021. It is important to note that the dataset reflects only those well records for which location information was available and comprises only 40% of total well drill reports to MGS. The point location of wells in the dataset was summarized within town boundaries to obtain the frequency of wells in the Maine towns, which is presented in Figure 21. The general spatial

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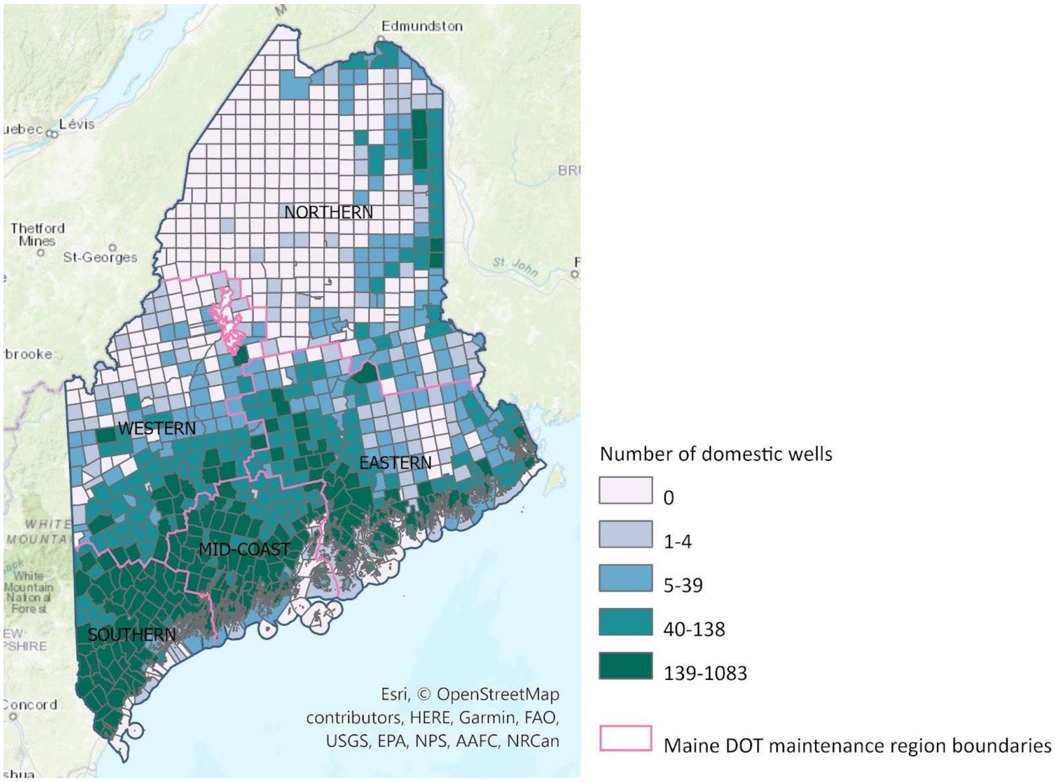
[6] Professor Shaleen Jain is the primary author on this section

distribution of wells appears to be linked to the population density, as well as factors such as presence of water supply systems. Nearly 40% of the residents of the state use private wells for water supplies. As such, water quality testing affords useful information to create baselines to assess presence of various chemical constituents.

Figure 21: Domestic Wells Drilled in Maine Towns, 1990–2021



Esri, © OpenStreetMap contributors, HERE, Garmin, FAO, USGS, EPA, NPS, AAFC, NRCan

In this report, the chloride concentration levels in Maine wells are assessed using well test data obtained from MaineDOT.[7] The data contains information on contaminant concentrations obtained from investigative sampling tests conducted in response to well contamination claims filed to MaineDOT and preconstruction sampling tests conducted along public roads. There are a total of 5,387 sample test records and 44 fields for each test record. These fields contain information on street and geographical address for well households or sampling locations, sampling date, well type and construction material, well depth, distance to road and septic tank, and sampling test results for 21 water quality parameters. The sampling date for the tests ranges from 2001 to 2020. In addition to chloride, concentration levels are also recorded for calcium, magnesium, nitrite, copper, iron, manganese, fluoride, arsenic, sodium, lead, ammonia, and uranium (Figure 22).

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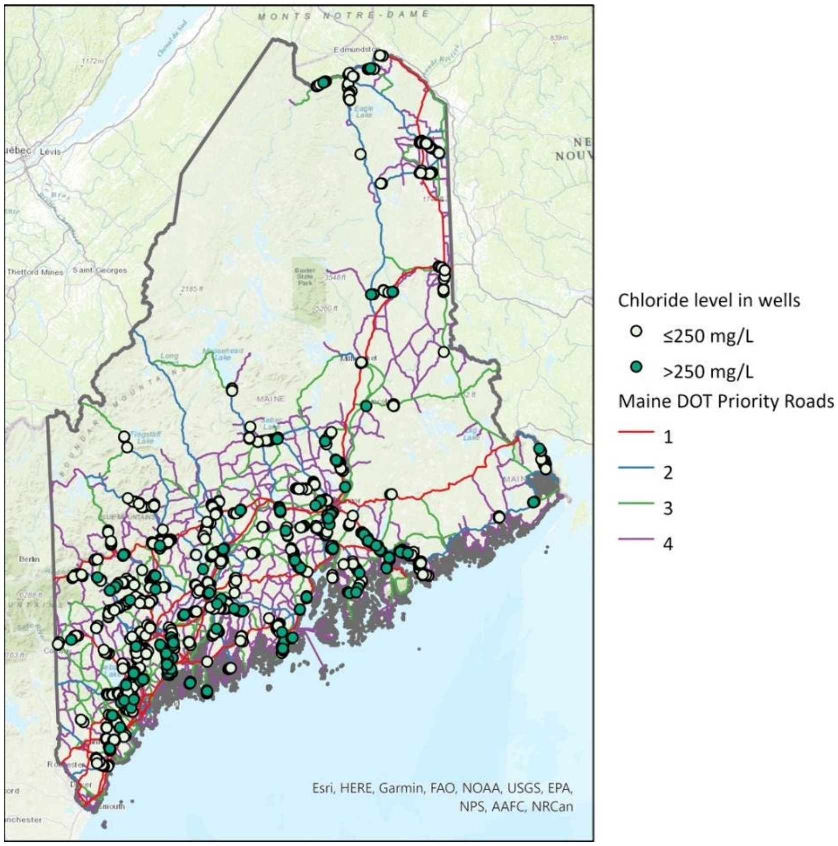
[7] In addition to this quantitative look at contamination based on MGS data, our survey of municipalities finds that respondents report that 16% of some municipal areas require special practices for winter maintenance, such as wetlands or public water supply. Additionally, 22% of respondents reported that they have had a well claim for salt contamination in their jurisdiction.

The dataset was screened for well location inside Maine and completeness of record based on chloride concentrations. Thresholds of contaminant levels for arsenic and chloride were adopted from US EPA's National Primary Drinking Water Standards (NPDWRs) and National Secondary Drinking Water Standards (NSDWRs). Maine CDC follows EPA's regulations for both arsenic and chloride in Maine public water systems. The Maximum Contaminant Level (MCL) for arsenic as enforced by the EPA's primary standard is 10 parts per billion (ppb) or 0.010 milligrams per liter (mg/L). This is the highest level of arsenic concentration that is allowed in public water systems. Potential health effects from long-term exposure to arsenic above MCL include skin damage, problems with the circulatory system, and increased risk of cancer.

Figure 22: Chloride Concentrations (mg/L) in Wells Sampled by the MaineDOT

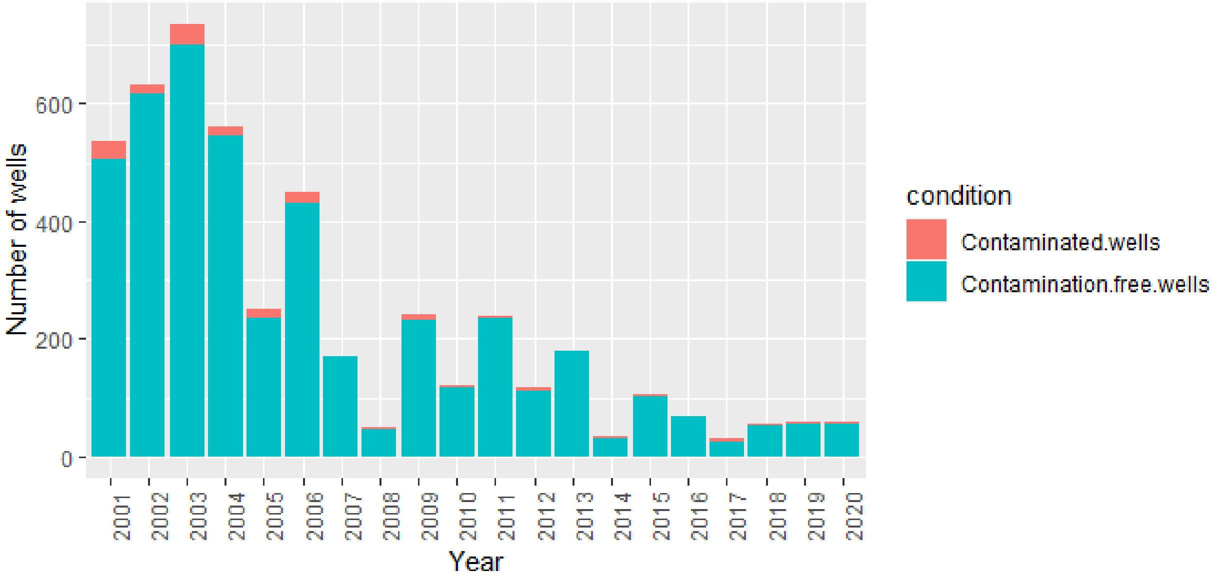


Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS, AAFC, NRCan

The Secondary Maximum Contaminant Level (SMCL) for chloride as recommended by the EPA's secondary drinking water standard is 250 mg/L. Since high amounts of chloride give a salty taste to water and corrode pipes, pumping, and plumbing fixtures, SMCL for chloride is set to indicate water quality concerns. The secondary standard is not enforceable but is recommended as a reasonable goal. Out of the 4,740 complete test records on chloride concentrations, 182 (3.8%)

tests show levels above US EPA's SMCL for chloride (250 mg/L). The results from testing indicate that cases of chloride contamination are concentrated in the Southern, Mid-Coast, and some parts of Eastern MaineDOT maintenance regions. A majority of tests were conducted during the 2000–2006 period, wherein the annual average exceeded 400 samples (Figure 23).

Figure 23: Well-Testing statistics over the 2001–2020 Period



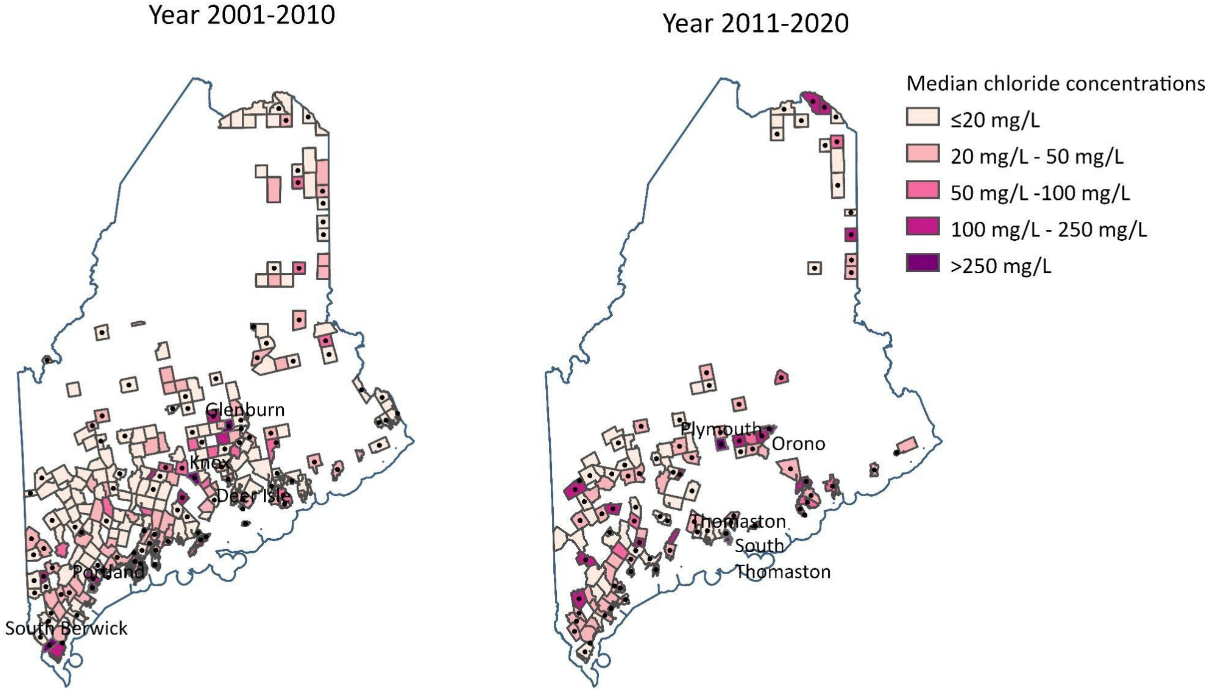
Relatedly, three-fourths of the identified cases of chloride contamination were identified during 2000–2006 (Figure 23).

It is worth noting that the collected samples span the state; however, they are a subset of the 76,643 identified well locations registered in the database maintained by the Maine Geological Survey. As such, analyses presented in this report require careful interpretation and should not be construed as representing the spatial patterns of statewide well contamination. The latter would require a systematically designed sampling approach, which is beyond the scope of this study.

Chloride contamination in Maine towns

The median chloride concentration in Maine towns over two periods (2001–2010) and (2010–2020) are presented in Figure 24. Values of chloride concentrations at wells lying within the individual towns were used to estimate the median. The towns with median chloride concentrations above 250 mg/L are labeled. Towns with fewer than five sampled wells are marked with black dots. During 2001–2010, 57 towns had at least one well test exceeding chloride SMCL. Town of Durham in Androscoggin showed the maximum number of contamination cases of 13 for this period. During 2011–2020, 15 towns had at least one well with a chloride concentration above SMCL. South Thomaston in Knox County showed the highest number of contaminated wells of 4.

Figure 24: Median Chloride Concentration in Maine Towns



Year 2001-2010

Year 2011-2020

During the first decade (2001–2020), towns of South Berwick, Portland, Knox, and Glenburn (left map in Figure 24) showed median concentrations of chloride above 250 mg/L. For the latter period (2010–2020), Thomaston, South Thomaston, Plymouth, and Orono (right map in Figure 24) were detected with contamination levels of chlorides. These results provide place-based estimates of elevated chloride concentrations. Improved sampling that spans communities and includes more towns can help to accurately identify the towns at risk of chloride contamination. Furthermore, town and MaineDOT region-level statistics were also compiled to assess the prevalence to chloride levels in wells exceeding SMCL.

Table 16: MDOT Maintenance Regions during Two Decades: 2001–2010 and 2011–2020

DOT Region	**Period 2001–2010**			**Period 2011–2020**		
	Domestic wells drilled	**Sampling tests**	**Tests with Chloride > 250 mg/L**	**Domestic wells drilled**	**Sampling tests**	**Tests with Chloride > 250 mg/L**
Southern	6,565	930	45	6792	396	11
Mid-Coast	3,915	938	36	3420	92	5
Western	2,616	626	13	2684	218	4
Eastern	5,070	849	45	3694	148	8
Northern	594	409	13	562	93	0
Statewide	18,760	3752	152	17152	947	28

Table 17 shows the number of Maine towns and cities showing chloride levels exceeding SMCL. across DOT regions. These 81 towns have at least one well with chloride concentration exceeding 250 mg/L.

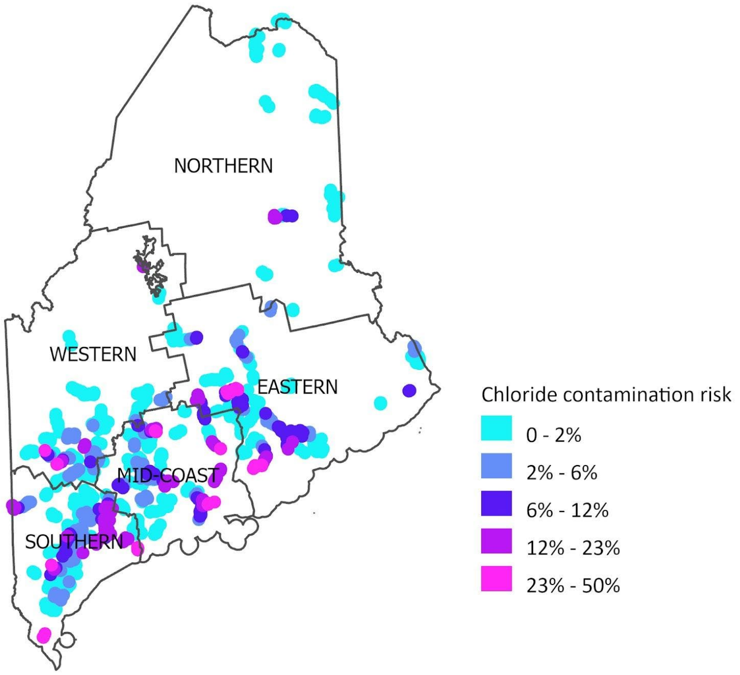
Table 17: Number Maine Towns Showing Chloride Contamination across MaineDOT Regions

DOT Regions	**First Class Cities, C: Population > 10,000**	**Second Class Cities, B: Population between 1,500 and 10,000**	**Towns, A: Population < 1,500**	**Total**
Eastern	1	11	10	22
Mid-Coast	2	14	3	19
Northern	0	0	5	5
Southern	8	14	0	22
Western	0	8	5	13
Statewide	11	47	23	81

Chloride contamination risk in study regions

We estimated the risk of chloride contamination at an area by dividing the number of wells exceeding 250 mg/L (secondary drinking water standard for chloride) by the total number of wells within the area. Risk estimates centered at well locations are computed as the proportion of tests wells within a 5000-meter radius (Figure). No risk estimates were computed for study areas with less than five wells. The quantified risk offers a limited view of the relative likelihood of spatially proximate sites with high contamination levels. While limited by the nature of sampling, a foreknowledge of local risk can be useful for estimating remediation strategies and guidance to local communities.

Figure 25: Localized Estimates of Chloride Contamination risk in the Study Area

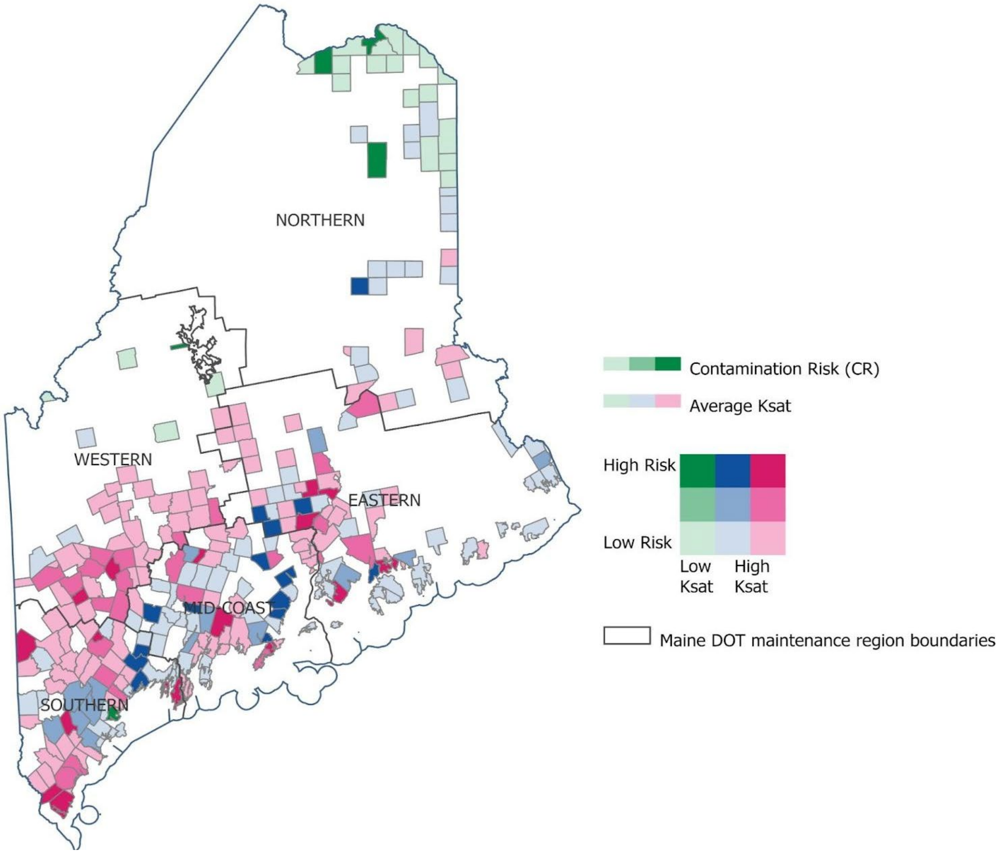


Chloride levels, hydraulic conductivity, and faults

The rate of transport of dissolved road salt within the soil layers is largely influenced by hydraulic properties of the layers. Hydraulic conductivity is a property of soil that describes the ease with which a fluid can move through pore spaces. Ideally, higher conductivity of subsurface layers implies higher infiltration rate. However, at times, other topographical factors, such as presence of bedrock fractures or distance to nearest salted roads, come into play and significantly alter the course and rate of infiltration. As for the concentration of chlorides, additional factors such as road salt loadings or dry or wet periods also bring spatial and temporal changes.

In this section, we aimed at investigating the correspondence between soil hydraulic conductivity and computed well contamination risk across Maine towns. Other factors that influence migration and transportation of road salts and presence of chloride include the thickness of sand and gravel layer, depth to bedrock, and well depth. The values of saturated hydraulic conductivity (Ksat) for Maine were obtained from the global Ksat map at 1 km resolution at depths of 0 cm, 30 cm, 60 cm and 100 cm made available by Gupta et al. (Gupta et al. 2021). Equivalent vertical saturated conductivity was estimated over the depth of 100 cm and averaged to obtain average Ksat for the towns. Our analysis of this is seen in Figure 26, which shows the bivariate choropleth map for changing chloride contamination risk and average saturated hydraulic conductivity (Ksat) in Maine towns.

Figure 26: Chloride Contamination Risk and Average Saturated Hydraulic Conductivity



We identified 19 towns, as represented by dark pink patches in that showed a distinct association between high saturated hydraulic conductivity and high well contamination risk. While local geological and soil characteristics are key determinants of the potential migration of road salt to groundwater wells, it is beyond the scope of this study to assess the causal connections between salt applications and elevated chloride concentration. Nonetheless, the statewide patterns of soil hydraulic conductivity and faults underscore the meditative role of local hydrogeological conditions, a topic that is worthy of future investigations (Figure 26). Preliminary assessment of the number of wells exceeding SMCL levels does not appear to show that proximity to known faults may increase the likelihood of salt migration.[8]

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[8] The Secondary Maximum Contaminant Level (SMCL) for chloride is 250 mg/L.

Figure 27: Saturated Hydraulic Conductivity: Wells with Chloride Exceeding SMCL

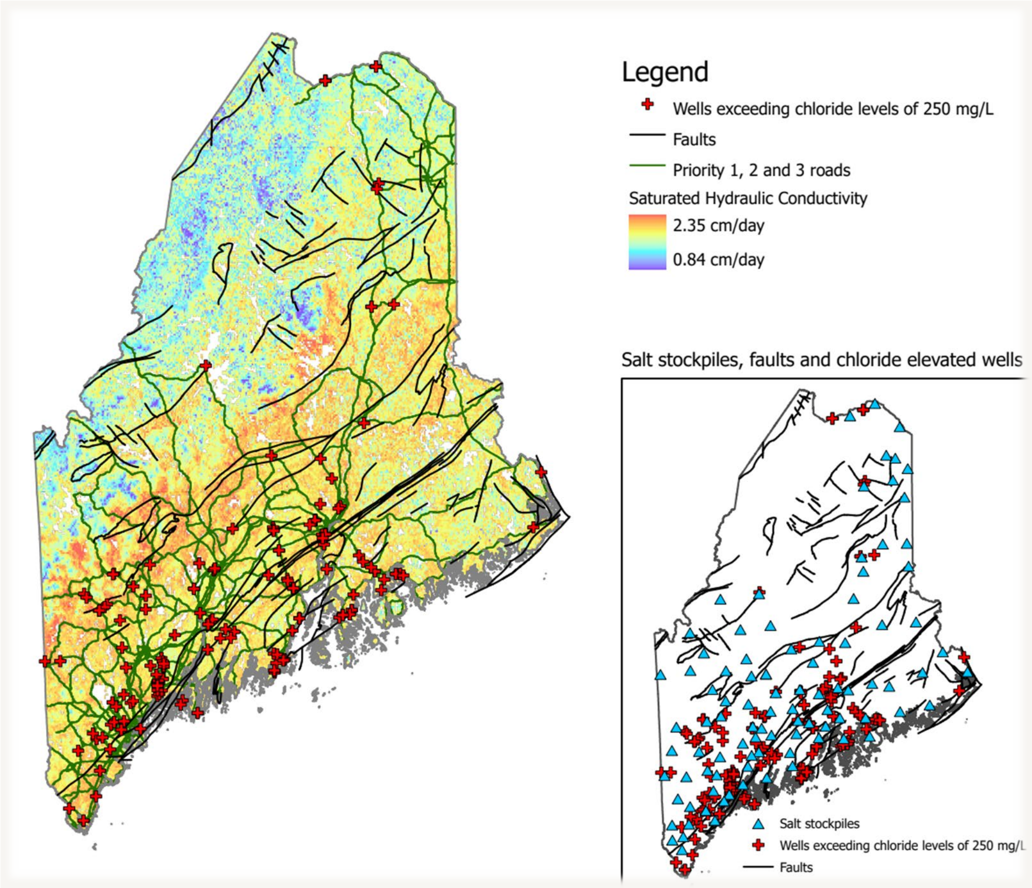

Figure 27 provides information on the conductivity of soil (measured as hydraulic conductivity up to 100 cm in depth) taking into account the location and span of bedrock fault lines and the location of salt stockpiles. The bedrock fault lines GIS data were obtained from Maine Geological Survey (MGS 2020).

Flows of aqueous road salt away from source (e.g., road salt loads) is driven by a combination of factors including roadside slope, soil hydrology, surficial and bedrock geology, and the presence and orientation of bedrock fractures. A recent study by Maine DEP investigated influence of the hydro-geological conditions on private wells in Maine (Holden and Hopeck 2021). Using a set of 2,245 well-sampling test data, they confirmed that wells that are down gradient from the road centerline are more likely to accumulate dissolved road salt. In addition, shallow wells with the capture zone downslope from road were found more likely to be contaminated compared to deeper drilled wells. This is due to a higher rate of water infiltration and short travel time. With deep wells drilled into bedrock, the inflow is mostly through the intricately connected fracture system and is challenging to characterize. Nevertheless, Holden and Hopeck found that a more optimal alignment between the dominant bedrock fracture direction and direction from road to well increases the soil hydraulic conductivity in groundwater in downslope compared to upslope.

Considering all factors the three highest and lowest risk categories obtained from the study are (in order) volcanic bedrock wells, dug shallow wells, and wells lying in 5 to 7 degrees of slope (well to road). The high risk denotes the greater likelihood of chloride contamination in downslope wells from road and lower chloride concentration for upslope wells. The lowest relative risks for wells are for those located in silt and clay, gravel, boulders, sandy loam and low-hydrologic soils.

Financial cost of well contamination

Under state law, MaineDOT is obligated to resolve well claims for any private water supplies that are destroyed or rendered unfit for human consumption by constructing, reconstructing, or maintaining of a highway, including the use of salts for winter road maintenance (Maine Revised Statutes 1971). Individual well claims are investigated to determine the validity of the concern. Data are obtained from laboratory analyses, geophysical studies, and hydrogeological evaluations to determine liability and identify appropriate remedies. Actions to resolve well claims are tailored to address specific issue(s); past efforts have included replacement water supplies, installation of water treatment systems, and property acquisition. MaineDOT has spent approximately $5.3 million since 2006 to investigate, assess, and resolve well claims (Doughty and Dwight 2022).

Maine's Changing Climate

Wintertime road conditions comprise a complex array of weather phenomena, ranging from icing, frost, frozen rain, to black ice, to name a few.[9] Thus, the amount and timing of salt application on roads is closely linked to winter weather severity. As such, numerous weather severity indices have been developed with a view to (a) anticipate salt usage, (b) interpret weather forecasts within the context of potentially hazardous conditions on roads, and (c) plan and schedule salt application on roads.

A study conducted by Strategic Highway Research Program (SHRP) in 1993 developed a severity index to help highway agencies efficiently allocate winter maintenance resources and ensure adequate safety (Boselly, Thornes, and Ulberg 1993). The SHRP index computes parameters for temperature, snowfall, and likelihood of frost based on daily weather records and provides a seasonal value varying from -50 (extreme severe and maximum ice and snow control) to +50 (warm and no snow and ice control necessary). The weights for parameters–temperature, snowfall, and likelihood of frost—in the equation are assigned according to their significance to the maintenance costs. Comparison of the index values with winter maintenance cost data from 40 states showed a strong log-linear relationship exists between cost and index. Since the development, the SHRP index has been actively used in the transportation agencies for more than two decades (Farr and Sturges 2012; Walker et al. 2019). The index is now actively used by Kansas and New Hampshire state DOTs for winter maintenance operations (Walker et al. 2019).

The Illinois DOT's WSI index is computed as the number of days requiring snow and ice work by summing the cold days and snow days (Cohen 1981). The formula for index computation is

$$W_{IIllinois} = D_{snow} + D_{cold}$$

Where D_{snow} is the number of days with snowfall accumulation greater than or equal to 0.5 inches (1.3 cm) and D_{cold} is the number of days with daily mean temperature between 15° F and 30° F (9° to -1° C). The index was developed by Illinois State Water Survey as a user-oriented climatic variable indicating the number of days when road salt is required. The index has also been incorporated into a study explaining the temporal and spatial variability of salt use on highways in the Province of Ontario, Canada.

The Accumulated Winter Season Severity Index (AWSSI) was developed in 2015 and intended for application in general sectors including transportation (Mayes Boustead et al. 2015). AWSSI is a point-based index that computes winter seasonal severity by accumulating points for daily values of minimum, maximum temperatures, and snowfall amounts and depths. Unlike other indices, which often compute seasonal severity based on fixed calendar months, AWSSI accumulates daily severity from an estimated onset day through estimated cessation day of the winter season. The winter onset day is defined as the day when any one of the three criteria are met: (1) daily maximum temperature ≤ 32° F (0° C), (2) daily snowfall ≥ 0.1 in. (0.25 cm), or (3) it is 1 December.

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[9] Professor Shaleen Jain is the primary author on this section.

The cessation day is when the last of the four conditions is met: (1) daily maximum temperature ≤ 32° F (0° C) no longer occurs, (2) daily snowfall ≥ 0.1 in. (0.25 cm) no longer occurs, (3) daily snow depth ≥ 1.0 in. (2.5 cm) is no longer observed, or (4) it is 1 March.

This allows the index to add points for the impacts of any offset or long winter season and accurately estimate seasonal severity. Once the accumulation period in winter is defined, daily points of AWSSI are computed based on thresholds of maximum and minimum temperature, snowfall, and snow depth. The point thresholds were designed to give greater weight to rare or extreme occurrences with trace snowfall and depths treated as zero not accumulating severity points.

Selected Weather Triggers for Road Salt Application in Maine

Ice formations on road surfaces are the result of freezing temperatures and moisture (water) availability on the surface. Although road ice formation during snowfall and rain is common, at times, moisture from the groundwater seepage as well as snow that had initially melted on the warm road surface also form ice if temperature lowers below freezing. In this study, we include four events leading to road ice formations and investigated their influence upon road salt use in Maine.

Freezing rain days

When falling rain passes through a below-freezing air layer near the road surface, it freezes into clear glaze ice as soon as it hits the road. Parameters corresponding to freezing rain have been included in several state DOTs indices and are also recognized as important in past indices developed for MaineDOT. In this study, freezing rain days corresponds to the days that receive rainfall and have daily mean air temperatures near freezing (25°F–32°F).

Frost days without precipitation

To account for the events when the moisture from roadside snow or groundwater seepage lead to road ice formations, we consider frost days without any form of precipitation. These were computed as the days when both the minimum air temperature and mean dew point temperature were below freezing temperature (32°F).

Snow days below and above freezing temperatures

Snow events were split into two subevents to investigate the extent of influence of snow days during freezing and nonfreezing conditions separately.

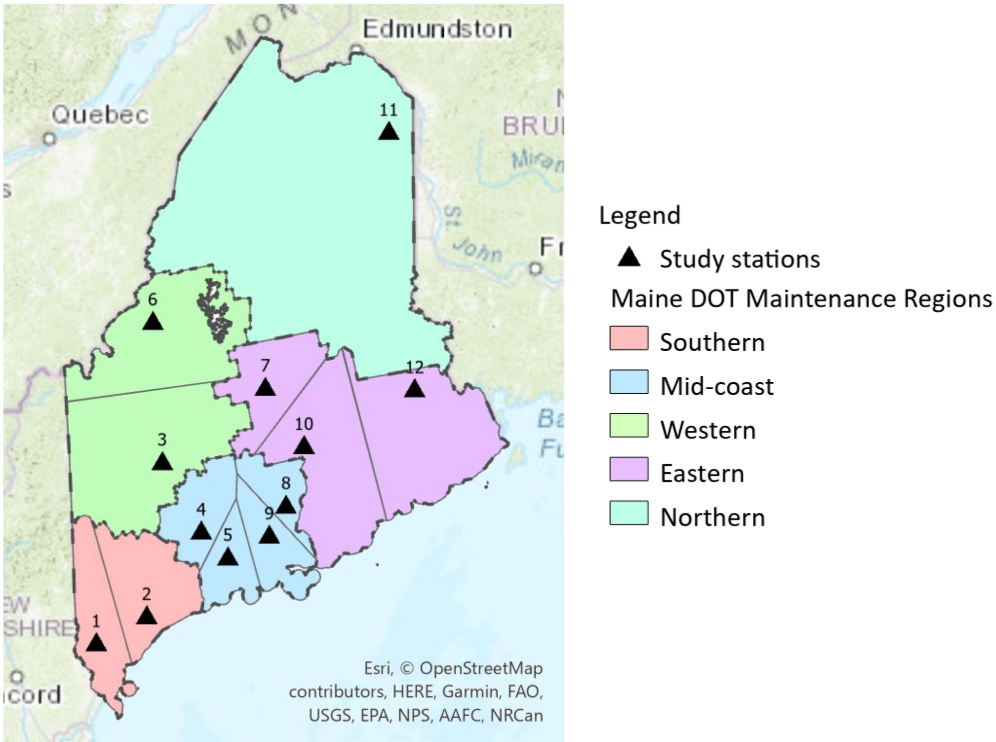
Climate Data

We collected daily meteorological data from the “cli-MATE” database maintained by Midwestern Regional Climate Center (MRCC 2021). To account for the spatial variability in climate conditions across the state, these data were collected at 12 stations spread in Maine: Sanford, Portland, Farmington, Gardiner, New Castle, Jackman, Dover-Foxcroft, Belfast, West-Rockport, Bangor, Caribou, and Grand Lake Stream. The selection was also governed by the data availability over the period of interest 1991–2020. Additionally, daily mean temperature, minimum dew point temperature, and precipitation values for the stations were obtained from PRISM (NACSE 2022). These additional data contributed to the estimation of frost events.

Study region and weather stations

To better understand climatic patterns during winter within DOT maintenance regions, the regions with multiple stations were divided into subareas as shown in Figure 18.[10]

Figure 28: Study station located across MaineDOT maintenance regions



Esri, © OpenStreetMap contributors, HERE, Garmin, FAO, USGS, EPA, NPS, AAFC, NRCan

Principal Component Analysis

Seasonal road salt use data were obtained from MaineDOT and reflected only MaineDOT's share of winter material use. Because the salt use data for regression was available as a statewide value, Principal Component Analysis (PCA) of the selected severity indices and metrics for values at 12 stations were carried out for dimensional reduction. PCA transforms the index values at these stations into new variables, designated as principal components, which are linear combinations of the original variables (index values at the stations). The linear transformation is performed in a way that the most significant variance in the original data is found on the first principal component, and each subsequent component is orthogonal to the last and has a lesser variance. In this way, the principal components obtained are uncorrelated and ordered so that the first few components retain most of the variation present in all of the original variables. In addition to dimension reduction, PCA is advantageous in identifying variables that are similar to and different

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[10] In regions with more than one meteorological station, smaller areas were delineated using Thiessen polygons.

from one another. Where many original variables correlate with each other, they will all strongly contribute to the same component thus allowing the identification of similar variables using the principal components.

Using Horn’s Parallel Analysis criterion, the number of components to be retained to capture maximum variance in the selected indices was either only one or two. Thus, the first two components that represent the severity at 12 stations were retained for each index. Regression models were then fit for natural log transformed salt use data using the retained components of the individual WSIs separately.

Relationship between Statewide Salt Use and Leading Winter Weather Indices

The two leading principal components for AWSSI, based on the 12 weather stations, explain nearly 80% of the total variance over the 1991–2020 period. The leading principal component represents the statewide pattern of interannual variability in wintertime weather. The second principal component shows long term trends towards increases in the AWSSI index, implying a higher salt use burden. The spatial pattern associated with the second principal components broad increases in AWSSI in the coastal climate zone (including Sanford, Bangor, and Grand Lake Stream). As such, a key interpretation from the analysis is the two uncorrelated patterns help parse the wintertime weather and climate variability into long-term changes and year-to-year variability. In total, the two leading principal components show linear relationship with the log-transformed salt use for the state of Maine.

Figure 29: Principal Component Analysis for AWSSI

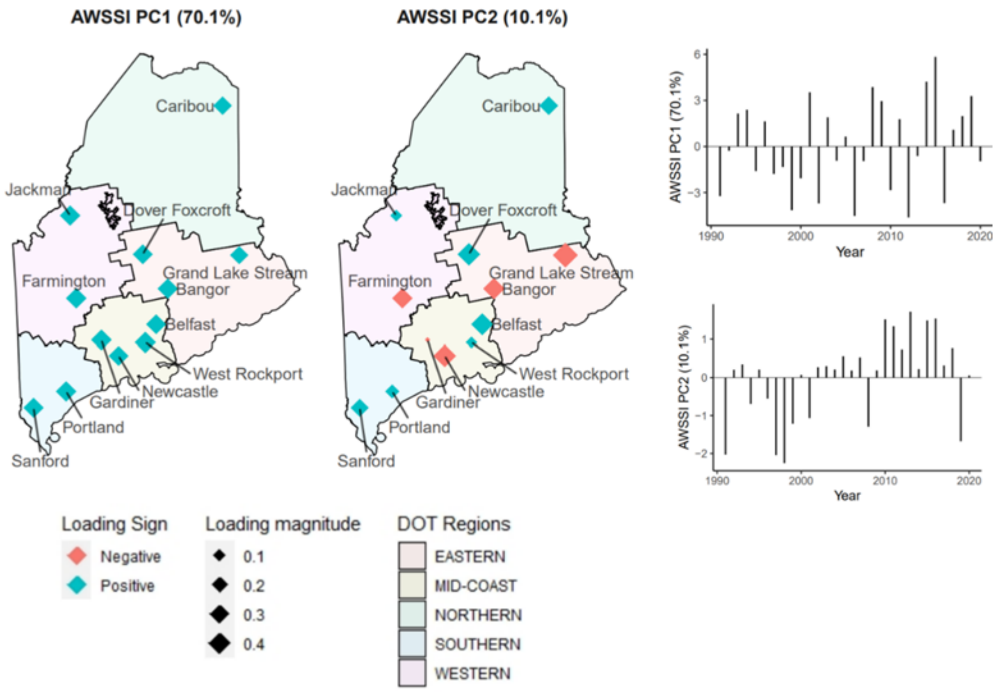
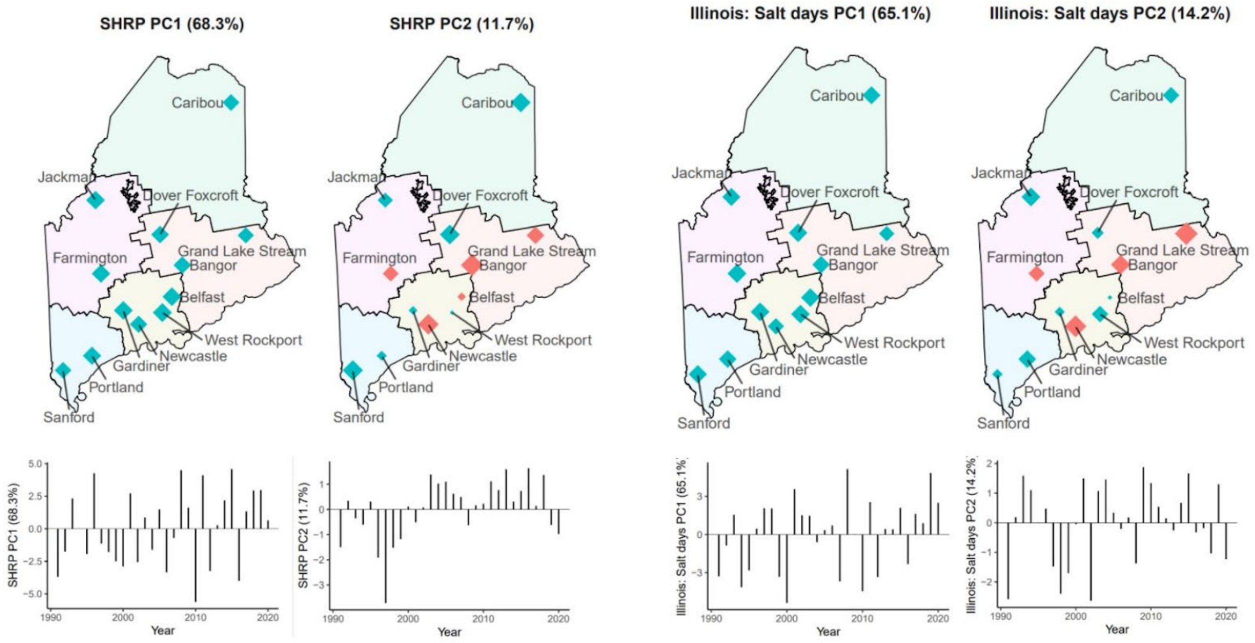


Figure 30: Principal Component Analysis for SHRP and Illinois Index



The principal component and linear regression analyses were carried out for two other weather indices (as shown in Table 18). These results are from the linear regression of seasonal MaineDOT salt use on suites of existing severity indices. In general, the three mode-based assessments show that the weather indices are important predictors of salt use, thus have high relevance for planning and decision-making. It is important to note that the salt use data shows response to winter weather and at the same time increased road miles and changes in the salt application practice. The statistical significance of individual predictors is noted below.

Table 18: Results Regression Results from Salt Use and WSI components

	Variance Explained (%)		**Regression Analysis 1991–2020**			
Weather Indices	**PC 1**	**PC 2**	**PC 1**	**PC 2**	**Time Year**	**R^2(%)**
AWSSI	70.1	10.1	0.026**	-0.072**	0.032***	84.5
SHRP	68.3	11.7	0.034**	0.014	0.027***	82.1
Frequency of salt days: WI_{Ill}	65.1	14.2	0.033**	-0.016	0.026***	81.1
Note: $p < 0.001$ (***); $0.001 < p < 0.01$ (**); $0.01 < p < 0.05$ (*); $0.05 < p < 0.1$ (+)						

The key findings from these regressions show that for the past 30 years, the AWSSI model explains 85% annual salt use variations.

Investigating the Selected Weather Triggers for Salt Use in Maine

Results shown in Table 19 are from linear regressions of seasonal MaineDOT salt use on selected weather triggers for salt use. Seasonal indices are computed from raw data for the 12 stations in Maine, followed by computation of principal components. For the analysis periods, 1991–2020, we provide coefficient estimates and the significance of predictor principal components, model performance in R^2 and model significance.

Table 19: Results Regression of Salt Use and Principal Components of Weather Events

	Variance Explained (%)		**Regression Analyses (1991–2020)**			
Weather Event Triggers	**PC 1**	**PC 2**	**PC 1**	**PC 2**	**Time (year)**	R^2(%)
Frequency of freezing rain days	46	13.5	0.036**	0.034	0.025***	80.2
Frequency of freezing days with snow	43.1	12.8	0.03	0.011	0.024***	75.1
Frequency of snow days above freezing temperature	57.5	10.4	0.032*	0.016	0.027***	79.6
Frequency of frost days no precipitation	74.5	6.5	-0.009	-0.008	0.031***	72.8
Note: $p < 0.001$ (***); $0.001 < p < 0.01$ (**); $0.01 < p < 0.05$ (*); $0.05 < p < 0.1$ (+)						

The four metrics of weather events show varying degree of relationship with salt use, with the frequency of freezing rain days and snow days above freezing temperatures showing the strongest relationship, explaining nearly 80% of the salt use variability. The relative differences in the statistical relationship also highlights that the weather triggers, when taken together, represent the diverse array of winter weather situations that merit attention within the context of salt use and transportation safety.

Nature of Changing Winter Weather Conditions and Severity over Last 30 Years

The method of quantile regression (QR) was adopted to study the long-term trends in continuous weather indices and conditions across different severity levels. Developed by Koenker and Bassett (1978), quantile regression estimates the functional relationship between predictor variables and any user-selected quantile in the response distribution.

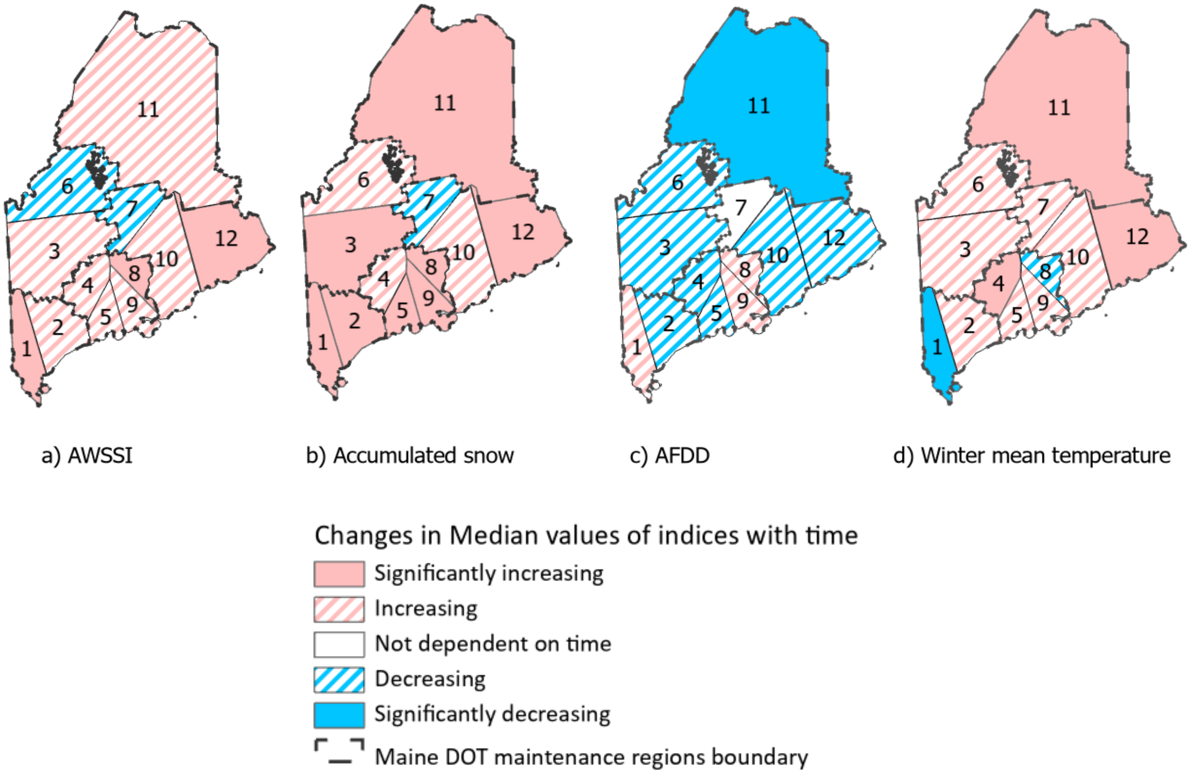
The historical records of climatic variables can be summarized by a probability distribution function (pdf) which provides estimates of frequency of occurrence of events (e.g., days < 32 F) within a given range and the probability of exceedance and non-exceedance of a given threshold value. The study of trends in the estimated pdf can help to assess the expected number of threshold exceedances, which are important in terms of impact of the event (e.g. days < 32 F) itself and forward planning mitigation and adaptation strategies. A traditional linear regression, suited to estimate the (conditional) mean, maintains the assumption of a constant variance among explanatory variables (e.g., temperature). It fails to acknowledge the natural variability across the distribution of the response variable. Hence, a linear regression assesses the symmetric changes in response variables *assuming trends observed in the mean are equivalent with trends across the* *distribution*. Quantile regressions, on the other hand, provide estimates of any conditional quartile (τ) of a response variable without any restrictions on the distributional variance. This allows for quantifying and identifying any opposing trends in median as well as lower and upper quartiles signifying the extremes of the distribution.

QR proves advantageous over conventional regression in our study due to its ability to detect opposing trends in statistical extremes as mitigation measures often need to be considered at different severity levels. For example, since high and low winter severity go hand in hand with degree of maintenance activity carried, any refined information on trends in the distribution of weather extremities is particularly useful in allocating and optimizing maintenance resources.

Trends in indices variability using quantile regression across key quantiles

The results for median regression obtained for seasonal indices AWSSI, accumulated snow, AFDD, and winter mean air temperature (1991–2020) are presented in maps in Figure 31. Significant trends are cases where the explanatory variable, time, is found to have statistically significant impact on the indices.

Figure 31: Trend Analysis Based on the Median Quantile Regression of Three Seasonal WSIs



a) AWSSI

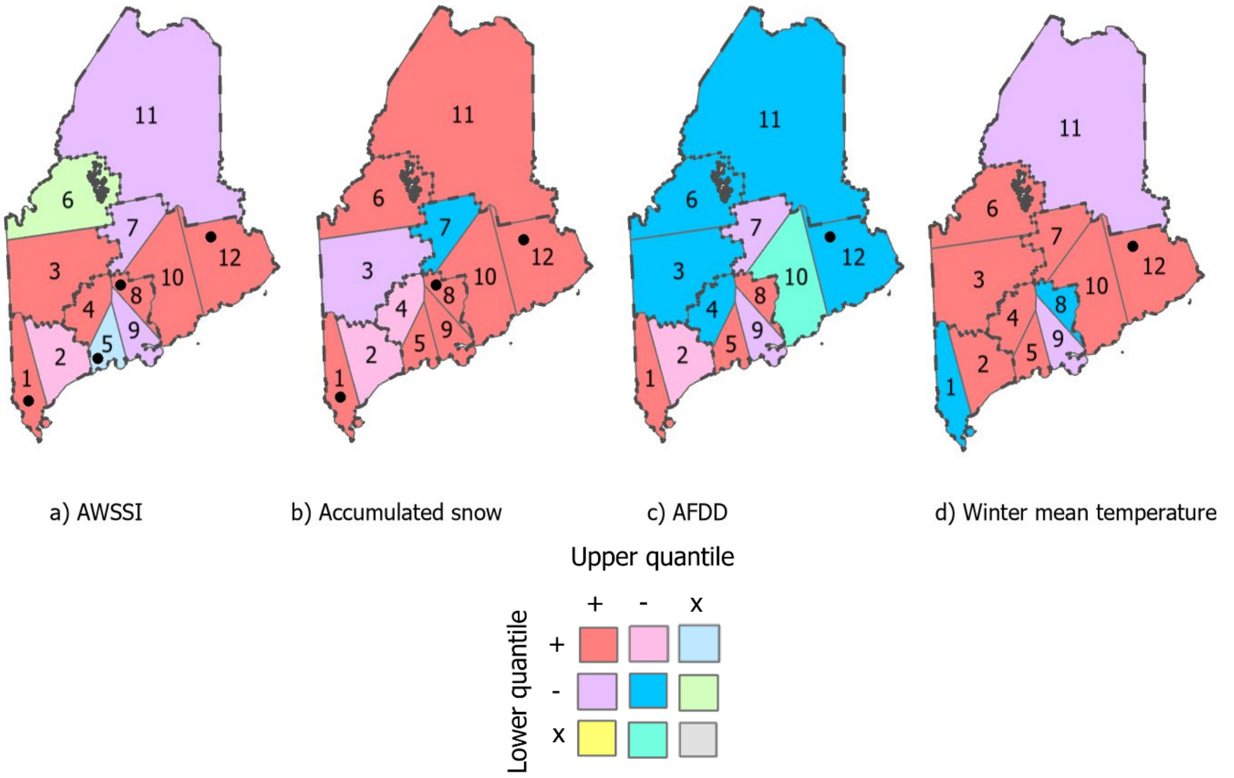
b) Accumulated snow

c) AFDD

d) Winter mean temperature

The long-term median trends show broad scale increases, except in the mid-interior region. As such, incidence of winter with higher AWSSI index are becoming more common and so is the accumulated snow. The modest overall trends towards warmer winters are evident in the trends for accumulated freezing degree-days and mean wintertime temperature. While trends in the median of the distribution of these indices offer useful insights, it is often the case that extreme events statistics may differ from median trends. To this end, an in-depth analysis of the trends in upper and lower portions of the distribution of indices was also pursued. The trends in upper (0.8) and lower (0.2) quantiles are shown. Regions showing statistically significant (p < 0.1) trends for both quantiles are marked with dots.

Figure 32: Trends: Extreme Lower and Upper Quantiles (0.2 and 0.8), four WSIs



a) AWSSI b) Accumulated snow c) AFDD d) Winter mean temperature

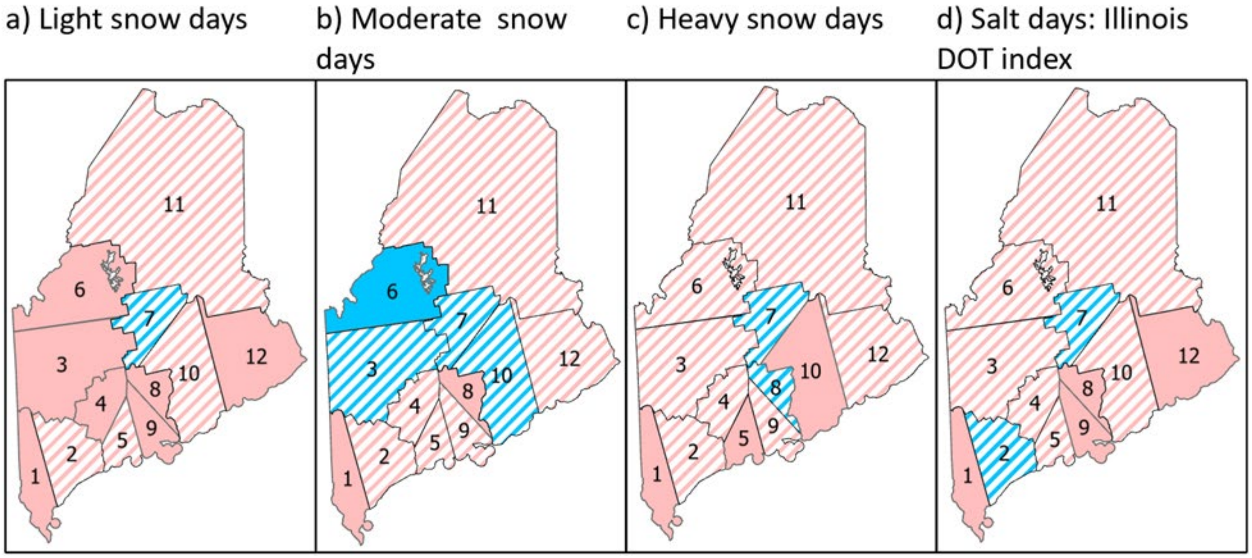
The trend typology (shown above) for the AWSSI index highlights that the increases seen in median quantile regression are mirrored for the upper and lower quantiles for Sanford, Farmington, Gardiner, Belfast, Bangor, and Grand Stream locations. However, the AWSSI trends for the upper quantile show increases for Caribou, but not for the lower quantile. These asymmetric trends in the extreme ends of the weather index distribution underscore an important concern for planning and decision-making, in that the trends in extreme have disproportionately large impact and careful consideration of the trends may allow for better planning and adaptation approaches.

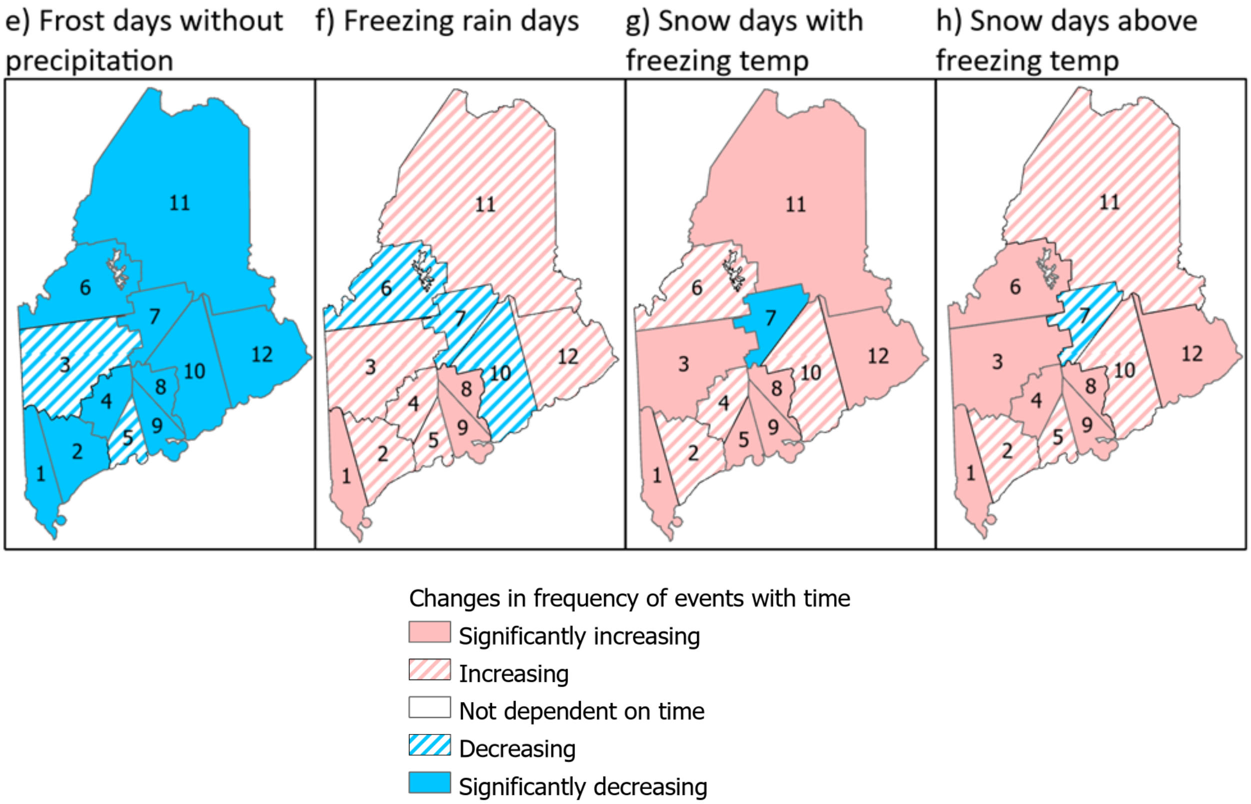
Trends in frequency of extreme events using Poisson regressions

For additional information on the nature of changes in cold and snow severity within the winter season itself, we performed quantile regression analysis on the monthly indices: mean monthly air temperature and monthly accumulated snow over years 1991–2020. The results for this section are provided in the appendix.

Count indices representing the frequency of weather events are analyzed using Poisson regression models (used for analyzing discrete data, e.g., 3, not 3.25 weather events). A quasi-Poisson regression, a special case of Poisson regression, is adopted to account for the unequal mean and variances in the WSI indices. Multiple models of quasi-Poisson regression are performed with count indices (number of discrete events) as the response (dependent) variable with the time variable, year, as an explanatory variable in each model. Since a positive coefficient estimate for the predictor, year, implies increasing counts of the response variable, e.g., weather event, we can observe the signs and significance of the coefficient for time variable to let us know how changes through time impacts weather events. The signs and statistical significance of the coefficient of time variable in each regression model is plotted in one of four categories (increasing, significantly increasing, decreasing and significantly decreasing).

Figure 33: Poisson Regressions of Season Indices for 12 Stations, Winters 1991–2020





The analysis of the trends in the frequency of wintertime weather conditions provide important complementary information that is missed in seasonal indices. Given that much of the salt use is carried out on an event-by-event basis, the count is a critically important measures of the severity and frequency of weather situations that demand close attention from a transportation perspective.

While frequency of three events—freezing rain days and snow days during both freezing and nonfreezing temperature—show general increasing trends from 1991 to 2020, frost days without precipitation have generally decreased across most regions. All regions except 3 (Farmington) and 5 (Newcastle) show statistically significant evidence of increasing events of frost days. Freezing rain days, which was found to relate to statewide salt use by R2 by 41%, appeared to increase significantly at regions 1 (Sanford), 8 (Belfast), and 9 (West Rockport). The regions 6 (Jackman), 7 (Dover-Foxcroft), and 10 (Bangor) showed decreasing but nonsignificant patterns of freezing rain days.

Both snow days during freezing and above-freezing temperature show similar trends across the locations. The central region 7 (Dover-Foxcroft) distinctly showing decreasing patterns of snow days. Most other regions show significantly increasing frequency of snow days.

Winter Maintenance in Selected States

More populous states with more roadway mileage have experienced greater impacts from road salt than Maine and have taken various policy approaches. The experience of other states can help Maine understand both approaching trends and the potential impacts of policy choices. We outline the cases of New Hampshire and Connecticut as well as notable elements of the experience of New York and Minnesota. For each, we take a brief look at road statistics, materials and practices, impacts, and policies.

New Hampshire

New Hampshire was the first state to use road salt for regular winter road maintenance in the 1940s. Currently the NH Department of Environmental Services (NHDES) acknowledges that **"**Dramatic and rising concentrations of chloride from salt applications have been identified in New Hampshire waters due to the application of de-icing chemicals" (NHDES 2021c). In 2013, New Hampshire also became the first state to implement a novel program to reduce road salt use by affording limited liability to winter contractors who receive training and register with NHDES to track their salt application rates. Since then several other northern states have proposed emulating New Hampshire's experience with contractor training and liability legislation.

Table 20: Comparison of Maine and New Hampshire with Focus on State DOTs

	Maine	**New Hampshire**
Population (2020)	1,362,359*	1,377,529*
Area	33,215 square miles	8,969 square miles
Political divisions	488 towns and cities 16 counties	234 towns and cities 10 counties
Population per square mile*	40.5	151.6
Registered drivers*	1,046,129 drivers	1,195,211 drivers
Mileage	46,736 Total lane miles 8,158 state lane miles (DOT) 36,729 municipal winter lane miles	33,391 Total lane miles 9,366 state lane miles (DOT) ~24,025 municipal winter lane miles
DOT winter cost/lane mile	$5,642	$5,750
DOT Salt use	155,568 tons	202,242 tons
DOT Liquid use	947,762 gallons	250,414 gallons
DOT Total snow & ice costs	$46,024,650	$53,858,736

Sources: *Population (US Census Bureau 2020b) (US Census Bureau 2020a);
*pop per sq. mile (Statista 2020);
*Cost per lane mile and material use and costs (Clear Roads 2019);
*road miles (US DOT Federal Highway Administration 2020) (NHDOT 2019);
*Registered drivers (Statista 2021)

The state of New Hampshire has a population similar to Maine, which is more densely settled, it has fewer total lane miles than Maine, more of which are state-maintained, and a similar cost per lane mile for winter maintenance of state roads. Table compared New Hampshire and Maine by DOT mileage, materials, and costs. Municipalities maintain nearly 70 percent of roadways in New Hampshire (NHDOT 2019). Road clearing materials differ, as do total snow and ice costs. Notably, New Hampshire DOT uses more salt and less liquid, and has a higher total costs for NHDOT winter road maintenance. Both consistently rank in the top ten nationally for cost per lane mile along with other New England states (Clear Roads 2021).

The statewide cost of winter snow removal on New Hampshire's state highways per storm is approximately $80,000. This includes all state equipment, hired equipment, labor charges, fuel, salt and sand. (NHDOT 2021a). NHDOT defines the five types of roadways below and their associated winter priorities based on snowfall accumulation and plowing frequency. Some 70% of mileage in the state is maintained by municipalities and municipal practices vary based on location, population, road density, and budget.

Table 21: New Hampshire Roadway Priorities

NH DOT Roadway Priority	Plowing Frequency	Allowable Accumulation
Type 1-A Interstate/Divided Hwy	1.5 hours	1.5–3"
Type 1-B Primary & Secondary	2 hours	2–4"
Type 2 Primary & Secondary	2.5 hours	2.5–5"
Type 3 Secondary	3.5 hours	3.5–6"
Type 4 Primary & Secondary Low Salt	2.5 hours	2.5–5"
Type 5 Secondary No Salt	3.5 hours	3.5–6"

Source: (NHDOT 2021b)

New Hampshire impacts

Salt use has nearly doubled in the past 40 years in New Hampshire to 190,000 tons per year or 21.5 tons/lane mile (NHDES 2013). Increasing levels of chlorides are being detected in groundwater and chloride impairments in New Hampshire streams are increasing (NHDES 2021b).

In 2008, New Hampshire listed 19 chloride-impaired water bodies on the 303(d) list under the Clean Water Act. By 2018 the list had risen to 40 streams, and by 2020 the number of streams increased to 50 with levels of chloride elevated enough to be harmful to fish and other aquatic life. The primary source of this chloride impairment is identified as road salt (NHDES 2021d).

An increase of chlorides and sodium in NH groundwater from 1960 to 2011 is documented in a USGS study that reports that median chloride concentrations were at least 1.5 times higher and sodium concentrations at least 3 times higher between 2000 and 2011 than in all previous decades (Medalie 2013).[11]

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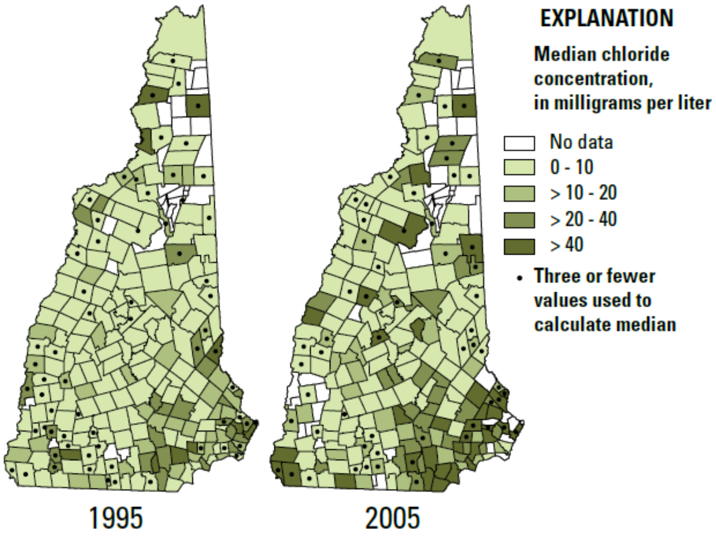
[11] Differences between the maps illustrate changes in chloride concentrations by town, see the original for additional detail (Source: Figure 1, USGS Fact Sheet: Concentrations of Chloride and Sodium in Groundwater in NH 1960-2011) (Medalie 2013)

Figure 34: Median Concentrations of Chloride in Groundwater in New Hampshire



In 2006, the expansion of Interstate 93 in New Hampshire prompted an examination of salt runoff. Water quality monitoring by NHDES, NHDOT, and the U.S. Environmental Protection Agency during the previous three winters documented concentrations of chlorides that did not meet water quality standards in water bodies located in four watersheds through which I-93 passes. The high chloride concentrations were largely due to winter road maintenance of paved surfaces, including I-93, state, municipal, and private roads, and parking lots on all roads in these watersheds. To address this issue, the NHDES and DOT performed a water quality and load reduction study, called a Total Maximum Daily Load (TMDL) study, in four watersheds to further assess road salt impact and then develop a comprehensive plan for winter salt use reduction (Burack and Stewart 2008).

NHDES monitored chlorides from 2008–2012 to track reduction. During this time, 89% of the total chlorides were found to be from de-icing sources. Calculations showed that a 25–45% reduction was needed to meet water quality standards. Source monitoring showed that the chloride amount was comprised of 45-50% parking lots, driveways and private roads, 30–35% municipal roads, 10–15% state roads. With ongoing chloride monitoring NHDES found that for 24% of the year the area was in violation of standards—most occurring in periods of low flow (NHDES 2021b).

NH policy: Contractor liability limits by legislation

With this salt reduction goal in mind, NHDES formed the 1-93 Salt Reduction Work Group consisting of state, municipal, and private sector representatives within the impaired watersheds to gain a better understanding of the snow and ice management industry. NHDES created *Green SnowPro* training based on existing salt reduction efforts in Minnesota. It includes using classroom training, hands-on training, and salt accounting. The goals included moving toward anti-icing (primarily by NHDOT), pre-wetting of salt, proper calibration and training. Voluntary training was offered to salt applicators who then passed a test to receive certification.

After implementing the voluntary training and certification program, it became apparent that contractors were worried about their legal liability for slip and fall events, leading some to over-apply salt to parking areas, driveways and shopping centers (Diers 2021).

As a result, the state enacted legislation in 2013 to provide limited liability to contractors. Under the Green SnowPro Program: RSA Chapter 489-C Salt Applicator Certification Option, salt applicators who receive training and pass the test may become certified annually by NHDES with renewal annually and a refresher course every two years. The refresher courses are offered by UNH Technology Transfer or by the Snow and Ice Management Association (SIMA), and can also be met by attending annual NH Salt Symposium (NHDES 2021a) Total salt usage must be logged into a salt accounting system. Applicators must also keep track of activities during each storm including application rates, weather, and sites visited in the accounting system.

Certified commercial applicators and owners or managers who hire them are granted limited liability protection against damages arising from snow and ice conditions, such as slip and fall lawsuits, under New Hampshire law (*Section 508:22 Liability Limited for Winter Maintenance.* 2013). NHDES encourages developers and contractors to develop a Salt Minimization Plan in addition to their winter maintenance plan.

To be eligible for the liability protection, master certificate holders are required to have their applicators trained, keep track of all salt use within their company, and complete the annual reporting every year. This system is designed to defend a company in the event of a slip-and-fall claim. Contractors can advertise their certification in their promotional materials.

While some municipalities have received the voluntary training, New Hampshire *cannot* certify municipal salt applicators under the current statute(NHRSA 2021). Municipal applicators who have attended the Green SnowPro training and have passed the exam are eligible to apply for the voluntary NHDES Salt Applicator Certification, but do not qualify for limited liability (NHRSA 2021). In 2020, a bill was proposed to extend applicator certification to municipalities, but this bill did not pass.

By 2019–2020, New Hampshire reported 517 state-certified salt applicator contractors. Each year, approximately 600 individuals are certified (NHDES 2021a). This is a first-in-the-nation program that many other states are watching for results. New Hampshire is working toward expanding the opportunity to certify municipalities in addition to contractors.

NHDES reports that there have been lawsuits involving slip-and-fall events, and some have been dropped because of the Green SnowPro program. Documentation of these lawsuits is difficult. The limited liability law has not been challenged in New Hampshire superior court (Diers 2021). Anecdotes point to contractors saving money on their winter maintenance and that “many contractors who become certified have been able to provide the same level of service and reduce their salt use by 30%” (NHDES 2020). The current tracking of salt applied by contractors year to year, however, is not precise enough to calculate overall savings (Diers 2021). Along the highly developed I-93 corridor where high chloride levels were first detected in surface waters, NHDES says New Hampshire has reduced its salt use by 20% from 15 years ago, though this may be due to multiple factors.

An unanticipated obstacle is the administrative burden placed on NHDES by the Green SnowPro program. NHDES must train and then track all trained applicators, resulting in significant time and cost for NHDES (Diers 2021). More funding partnerships would help reach more of the salt applicators, improve equipment, and assist municipalities in implementing the program. As another way to foster professionalism within the industry, NHDES and the University of New Hampshire offer an annual New Hampshire Salt Symposium, which provides communication within the profession and opportunities for training and recertification.

The Green SnowPro program is well liked in New Hampshire and is not controversial now, but there are still barriers to implementation and a need for more outreach to the public. They suggest that a grassroots approach to training could help empower local communities. The cultural expectation of bare pavement in winter is still a difficult barrier to overcome. One of the major impacts of enacting the limited liability for certified contractors has been to raise awareness of the salt issue and elevate the level of discussion among the various entities. It has caused some contractors to reduce their salt use, trained many, and brought the issue to attention of the public.

Other states with similar training programs for winter contractors include Minnesota, Wisconsin, and Connecticut. Legislation to establish programs modeled on New Hampshire's Green Snow Pro training and contractor limited liability have been proposed in some other states, but not passed.

Connecticut

Connecticut has a road mileage similar to Maine within a much smaller geographic area and a greater population density. The CTDOT cost per lane mile is much lower than that of MaineDOT as would reasonably be expected given that Connecticut's highest area of weather severity in the state corresponds with Maine's lowest area of winter severity. Therefore, a much lower cost per lane mile would be reasonably expected. The ratio of Connecticut's state to municipal roadway network lane-miles is 0.31; Connecticut's 169 municipalities are responsible for the maintenance of 82% of the state's total centerline roadway network miles.

Table 22: Comparison of Maine and Connecticut with Focus on DOT

2019	**Maine**	**Connecticut**
Population	1,362,359	3,565,287
Area	33,215 square miles	4,845 square miles
Political Structure	488 towns and cities 16 counties	169 municipalities 8 counties (no county gov't.)
Population/sq. mi.	40.5	735.8
Licensed Drivers*	1,046,129	2,608,061
Mileage	46,736 total lane miles 8,158 DOT lane miles 36,728 municipal winter lane miles	45,916 total lane miles 10,870 DOT lane miles 35,231 municipal winter lane miles
DOT Winter Cost/Lane Mile	$5642	$2140

2019	Maine	Connecticut
DOT Salt Use	155,568 tons	172,958 tons
DOT Liquid Use	947,762 gallons	503,398 gallons
DOT Total Snow & Ice Costs	$46,024,650	$23,260,950

*Population (US Census Bureau 2021b), *Drivers: (Statista 2021), *Mileage (Larsen, Bernier, and Mahoney 2020),*Materials and Costs (Clear Roads 2019)*Population (US Census Bureau 2021b), *Drivers: (Statista 2021), *Mileage (Larsen, Bernier, and Mahoney 2020),*Materials and Costs (Clear Roads 2019)

Connecticut, like other New England states, is a member of the 38-state national pooled funds study, "Clear Roads," under the lead of Minnesota DOT. This national research consortium focuses on testing winter maintenance materials, equipment and methods for use by highway maintenance crews.

Level of service

CTDOT's winter maintenance duties cover three categories: limited access highways, primary routes, and secondary routes. They also maintain commuter parking lots and other state facilities. Their annual winter maintenance budget is based on 12 storms per year, and in 2020 they reported a five-year average of $32,898,070 (Clear Roads 2021). CTDOT divides road priorities into three classes, shown in the table below.

Table 23: Levels of Service Connecticut DOT

Class	Description	Service
Class 1	Limited Access Highways – Includes interstates, parkways and expressways with corresponding ramps.	Continuous service throughout the storm with multi-truck echelon plowing and material applications; applications are made as necessary for reasonably safe travel and prior to rush hour periods. Lanes and shoulders scraped down to near bare pavement; snow accumulations will occur during periods of heavy snow; desired cycle time of two hours with a goal to have lanes cleared to bare and wet pavement within four hours following a winter event.
Class 2	Primary Routes – Includes major and minor collector highways;	Continuous service throughout the storm with two truck echelons; application on centerline with one wheel path of traction in either direction; lanes scraped down to near bare pavement; snow accumulations of 2 – 4 inches will occur during periods of heavy snow; desired cycle time three hours with a goal to have lanes cleared to bare and wet pavement 4-6 hours after a winter event.
Class 3	Secondary / Miscellaneous Routes – Includes low-volume, state-maintained roadways;	Continuous service throughout the storm with one assigned plow; application on centerline as needed, with attention to hills, curves and intersections; snow accumulations of over four inches may occur during periods of heavy snow; cycle time may exceed three hours; goal is to have the lanes cleared to bare and wet pavement within six hours following a winter weather event.
Source: (Connecticut Transportation Institute, UConn et al. 2015)		

Operations

Like other New England states, CTDOT moved to an anti-icing policy between 2006 and 2011, which reduced the amounts of sand used on state roads, along with the cleanup and related cost, but increased the overall amount of salt used. CTDOT has divided the state into seven geographic weather zones for planning winter operations. CTDOT uses specialized technology, Road Weather Information Systems, and driver training to reduce salt use. Currently CTDOT uses blend of MgCl for pre-wetting salt and strategically pre-treats 300 lane miles with brine, including bridges, ramps, and microclimates.

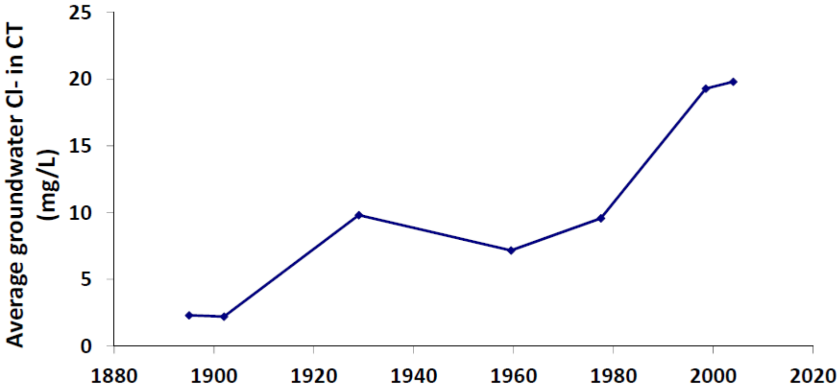
CTDOT maintains about one-quarter of the state's public roads, or 10,800 lane miles, while municipalities maintain 35,231 lane miles (76% of the total). Seventy-six percent of daily vehicle miles of travel occur on the 18% of the roadway network maintained by the state. Estimates of total salt use over five years from a municipal survey indicate that two-thirds of the state's total salt is applied on municipal roads. The same survey estimates total de-icer use on Connecticut roads at 710,511 tons in 2013–14 (Connecticut Transportation Institute, UConn et al. 2015).

This total does not include salt applied on shopping centers, parking lots, and sidewalks by private firms. While difficult to know the actual amounts, just as in NH, some suggest that a large portion of the overall state salt usage comes from private contractors (Hewitt 2019).

Connecticut impacts of de-icing

A study examining trends in groundwater chloride concentrations in Connecticut over the past 100 years documents the impacts of road salt on groundwater, noting "increased reliance on salting for de-icing, combined with the increasing urbanization of Connecticut, has led to an increasing influx of salt to Connecticut's groundwater." The average groundwater chloride concentration is steadily increasing (Cassanelli and Robbins 2013).

Figure 35: Connecticut Groundwater Chloride Concentrations

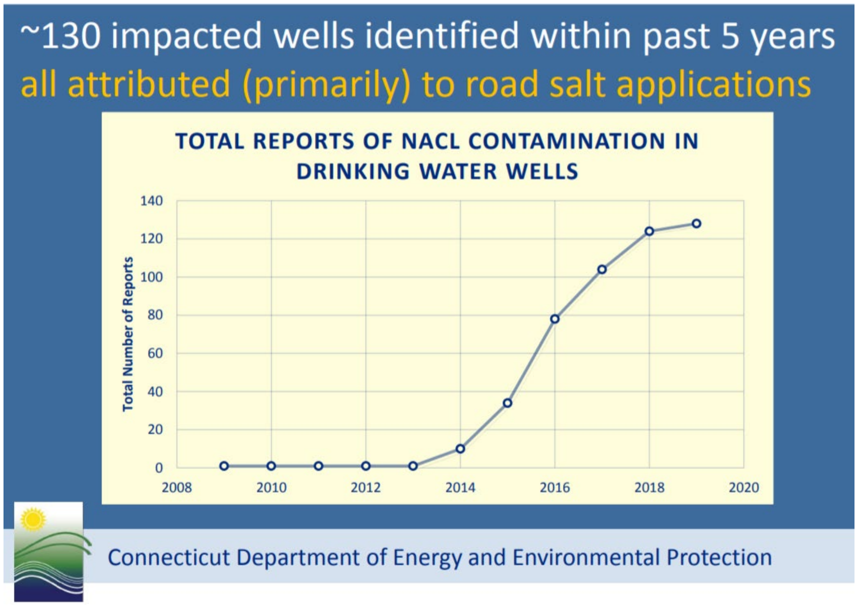


From Cassanelli & Robbins, 2013

Chloride concentrations are shown in ppm from the 1890s to 2007. Researchers found that areas of higher chloride concentrations correspond to more developed areas and to major highway corridors, which may indicate that groundwater chloride concentrations are due more to the influx of salt than to accumulation in groundwater storage.

The CT Department of Energy and Environmental Protection reports a statewide increase in sodium and chlorides in groundwater and surface waters. From 2014 to 2016 there were 50+ impacted wells identified. Then between 2014 and 2019 approximately 130 drinking water wells were reported contaminated and attributed to road salt application. Typical concentrations found were sodium = 200 – 400 mg/L and chloride = 400 – 900 mg/L (Drew Kukucka, CT DEEP 2019a).

Figure 36: Connecticut Well Impacts



~130 impacted wells identified within past 5 years

all attributed (primarily) to road salt applications

Connecticut Department of Energy and Environmental Protection

Source: (Drew Kukucka, CT DEEP 2019b)

Policy approach: Salt applicator training in Connecticut

Given the success of the Green SnowPro program in NH, Connecticut adapted the program, offering a pilot of the Green SnowPro training at the University of Connecticut (UConn) in November 2017. Salt reduction was found in the pilot program on UConn campus (Dietz 2020). Findings showed that, extending this reduction campus-wide, the university saved $459,251 in the two years after the training by applying 3479 fewer metric tons of salt.

Statewide implementation of the Green Snow Pro program began in the fall of 2018 as the CT Training and Technical Assistance Center (T2) gave two trainings for municipal public works crews. The “Green Snow Pro: Sustainable Winter Operations” training session has been offered six times.

CT DEEP plans to continue the Green Snow Pro program. Their version of the program is focused on municipal operations and roads, with some additional time spent on sidewalks and parking lots. They have plans for a version focused on contractors, but without the incentive of reduced liability like NH or a legislated requirement for the training, and as a grant-funded program, they don’t currently have the ability to expand the training focus to private contractors (McCarthy 2021).

Supporters of the program continue to meet to work on the issue of offering liability protection in Connecticut, as well as the expansion of the offering to private contractors. Anecdotal results indicate that towns are using less salt as a result of trainings, but there has not been a systematic assessment and the program has been limited in expansion by lack of funding (Dietz 2021).

Legislation was introduced in 2020 to provide more availability of Green SnowPro training in CT—*An Act Concerning Training Standards for Road Salt Applicators CT SB00097*. The bill sought to provide at least one voluntary training of the Connecticut Green Snow Pro certification program for state, municipal, and private road salt applicators in each county in the state and require the establishment of a low/no-salt standard in areas draining into public drinking water reservoirs (CTI UConn et al. 2015). The bill did not pass, but discussions are ongoing.

At the same time, a comprehensive statewide study recommends to continue using salt in spite of its impacts while working to limit these impacts by following best management practices. Recommendations include that Connecticut should develop a public information campaign, a program for voluntary certification of contractors with NH program as model, provide training, consider revising the level of service, and should consider developing a winter severity index and a road condition index (with Utah as an example). The report acknowledges the large percentage of winter maintenance performed by private contractors, the actual quantity of which is unknown, and the opportunity to reduce salt use by addressing this group. They also suggest that revising level-of-service classifications may be a cost-effective way to address the impacts of chloride de-icers (CTI UConn et al. 2015).

New York

With winter conditions similar to other New England states, higher population, and more road miles, New York State has historically been one of the largest users of road salt in the country and is now enacting policy measures to reduce salt applications. In parts of the state, NYSDOT has a “clear wheels” policy rather than bare roads policy. This means the measure of a clear road after a storm is two wheels of a vehicle contacting bare surface.

NYSDOT is part of Clear Roads, a national consortium of DOTs that sponsors pooled fund studies on winter maintenance topics. NYSDOT has pilot projects in the Adirondack region for testing salt reduction and lower speed limits. They have seen meaningful salt reduction in these pilots programs, particularly by using all-liquids (Lake George Association 2021). The NYSDOT has two statewide working groups that convene regional roundtables to meet with municipalities, contractors, other state agencies, and citizen groups on the issue of salt reduction.

State strategy

At the statewide level, in December 2020, the governor of NY signed on to the creation a three-year pilot program to reduce road salt in Adirondack Park, establishing a salt reduction task force to conduct a comprehensive review and a test program to be conducted by DOT with DES on all state-owned roadways within the Adirondack Park (9,375 mi^2). In the NY legislature, S8663/A08767 established the Adirondack road salt reduction task force, pilot plan, and test program. The task force should produce a report to include the scope of impacts and recommendations for salt reduction. As of September 2021, this task force and three-year pilot program have yet to be created, the delay due to COVID and the change in state administration.

In a separate approach, currently before the Senate Transportation Committee in the current Legislative Session (2021–22) is S657/A4066, which would amend the Transportation Law to create a road salt applicator training program. This legislation would create a voluntary training program for salt applicators to help minimize the negative impacts of chlorides, create a process for certifying applicators, and produce findings regarding liability relief for certified applicators.

NY Adirondack area: Seeking a regional approach

The Adirondack Park is the largest protected natural area in the lower 48 states, encompassing roughly 2 million acres of mixed public and private ownership. It includes more than 3,000 lakes and 30,000 miles of streams and rivers as well as 10,555 lane-miles of paved roads. Within the park, NYSDOT uses 2.5 times as much road salt as towns use, even though state roads comprise 27% of total mileage within the park, according to the Adirondack Council (Adirondack Council 2020). Monitoring in the Lake George basin is part of a NYSDOT road salt pilot program. A 30-year report on water quality shows that sodium and chloride in Lake George increased three-fold between 1980 and 2009 with higher levels in some tributaries feeding the lake, concluding that de-icing practices are the primary source (Sutherland et al. 2018; Swinton, Eichler, and Boylen 2015).

Recent research conducted by the Adirondack Watershed Institute and partners found that in testing over 500 private drinking wells in the Adirondack Park, sodium levels in more than half of the wells near state roads exceeded New York’s drinking water quality guidelines. One in four wells that receive state road salt runoff exceeded the state’s water quality standards for chloride (Adirondack Council 2020).

In addition to NYSDOT efforts, towns in the Adirondack region are taking local action to reduce road salt use. Warren County and the towns of Hague and Lake George are part of the Lake George Salt Reduction Initiative coordinated by the Lake George Association (LGA). The LGA has identified road salt runoff as one of the greatest threats to the water quality of the lake and other area waterways. Successes have been seen in some municipalities that are working with the state and local environmental groups to reduce road salt use with new equipment, new tracking techniques, the use of brine, and training. The town of Hague has reduced its salt use by 50% and its winter maintenance budget by 45% (Hall 2021). This reduction comes five years after their initial investment. The town of Lake George has reduced road salt expenditures by 50% since implementing a brine program. Some of the best practice techniques used by towns in the Lake George area are pre-treating roads with liquid brine in advance of winter storms to minimize ice buildup; using “live edge” plows, which conform to the shape of the road, to remove snow closer to the road surface; calibrating equipment monthly; and equipping their plow trucks with GPS and special software to track salt application and monitor road conditions (Arnold 2021; Lake George Association 2021). In their salt reduction efforts, both NYSDOT and Adirondack municipalities note the importance of communication with the public regarding salt reduction and winter driving practices.

Minnesota

Like other northern states, Minnesota has documented chloride-impaired bodies of water, noting 50 statewide in 2019 and another 110 which are close to the freshwater limit of 230 mg/L of chloride (MPCA 2019). Groundwater impairments are also increasing: 27% of monitoring wells in the Twin Cities metro area's shallow aquifers had chloride concentrations that exceeded EPA drinking water guidelines (MPCA 2016). A statewide chloride budget found that while fertilizers and wastewater treatment plants contribute salt into the urban environment, road salt use was the single largest contributor to chloride pollution statewide (Overbo, Heger, and Gulliver 2021).

Salt reduction policies

Minnesota is a national leader in chloride reduction efforts. In 2020, the MPCA developed a comprehensive Statewide Chloride Management Plan, which details areas of chloride loading, trends, and a strategy to reduce salt use (MPCA 2020). Minnesota offers trainings, salt assessment tools, model contracts for snow removal contractors, and model policies for chloride reduction for towns and cities. They also provide case studies of chloride reduction and cost savings in both municipal and private settings with web-based resources to road professionals as well as homeowners (MPCA 2021). The chloride management plan incorporates "Smart Salting" trainings directed toward property managers and local government decision makers, individual trainings for maintaining roads or parking lots and sidewalks, and certification for organizations that assess their salt use and take steps to minimize it. The Smart Salting Assessment tool is a resource of all known salt-saving BMPs to help organizations identify opportunities to improve practices, reduce salt use and track progress (MPCA 2021).

The MPCA and MnDOT have developed resources aimed at reducing salt use for road authorities, property managers, and citizens. These include model ordinances for cities to reduce chlorides, a comprehensive list of online resources to reduce salt use, a Statewide Chloride Management Plan, and a voluntary training and certification program on Smart Salting. Training is offered to individuals and organizations and is designed with two branches—one for roads and one for sidewalks and parking lots. Applicators certified in Minnesota's Smart Salting training report reductions of 30–60% in usage in their first year after training, and municipalities have documented the cost savings to their public works operations (MPCA 2020).

A coalition of organizations, including the citizen group Stop Over Salting (SOS), is working together to advance chloride reduction legislation, using a voluntary certification approach. In Minnesota, bills to provide limited liability to commercial applicators were introduced in 2016 and 2017. Minnesota's proposed legislation has been patterned after New Hampshire. In 2020, Minnesota introduced a bill establishing a certified salt applicator program, limiting liability—SF 1667 (2020), based on the NH model.

Traffic Safety Analysis and Winter Weather

In Maine, lane departure crashes are the leading cause of over 70% of roadway fatalities.[12] The majority of roadways in Maine are rural. Compared to other New England states, Maine has the highest roadway fatality rate (Bouchard, Bizier, and Kuchinski 2020). Maine also has aging infrastructures and experiences the third coldest weather. Despite an 18% decrease in average daily traffic volume, the half of the year with colder weather (November to April) comprises over 64% of the yearly lane departure crashes. Maine also has the oldest population in the U.S. (Himes and Kilduff 2019). The population has been showing an aging trend since the 1990 census, where the median age was 33.9 years old, and the U.S. median was 32.9 years old (Meyer 2001). The current median age in Maine is 44.6, and the median age in the U.S. is 38. The number of licensed drivers aged 65 or older in Maine has also continued to grow, from 17.8% of the total licensed drivers in 2010 to 24.8% in 2019. Younger drivers (ages 16–29) accounted for 20.2% of all Maine licensed drivers in 2010 and only 16.9% in 2019.

This section explores to what extent seasonal (i.e., winter vs. non-winter) and monthly weather variations impact lane departure crashes on rural Maine roads. This section also analyzes the impact of roadway, driver, and weather factors on the severity of single-vehicle lane departure crashes occurring on rural roadways in Maine. Four facility types—interstates, minor arterials, major collectors, and minor collectors—are considered for analysis.

Impact of Seasonal Weather on Frequency of Rural Lane Departure Crashes

Roadway crashes are caused by various factors, and understanding their causes is an essential step towards improving safety across roadway networks. Among all crash types, lane departure crashes are the leading cause of crash fatalities in Maine, accounting for over 70% of all roadway fatalities. Most of these crashes (64%) occur during the winter period, which in Maine spans from November to April. This study explores the impact of different weather variables on frequency of lane departure crashes (i.e., crashes described as went off road, head-on, or those that rollover is primary event) on rural roads in the state of Maine from 2015 to 2019.

Maine's location, land use, and terrain means it has unique features that are not comparable to other U.S. states. The state experiences all four seasons, with fluctuating weather year-round. Maine has a diverse geography, from the lengthy coastline surrounded by the Atlantic Ocean to the mountainous terrain from the Appalachian Mountain Range. Due to the significant differences, the weather from east to west or from north to south varies substantially. The state ranks as the *third coldest in the U.S.*, with an average yearly temperature of 41ºF (World Population Review 2021). Coastal Maine experiences an average yearly temperature of 43.8ºF, whereas northern Maine experiences an average yearly temperature of 38.2ºF (Fernandez et al. 2020). Though it is comparatively small in area, ranking as the 39th largest state in the U.S., the regional differences in weather in Maine vary greatly (US Census Bureau 2021a). The winter

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[12] Dr. Ali Shirazi is the lead author for this section.

season is long and can occur during at least half of the year. However, it is not uncommon for below freezing temperatures or winter storm events to persist through May or begin in late October, especially in the mountainous or northern regions.

As climate continues to change, Maine is experiencing more severe and diverse storm events. Though overall the warmer air and ocean temperatures are causing less snow accumulation, the trend is not linear. From 2010 to 2019, Maine regions have experienced record low and record high snowfalls. During the 2009–2010 winter season, northern Maine experienced 64 inches of snow, where the average snowfall is 110 inches per winter season. During the same winter period, the coastal region received 37 inches of snow, where the average is 60 inches per winter season. In terms of record high accumulations, during the 2018–2019 season, northern Maine set record snowfalls, as well as a record of 163 consecutive days with at least one inch of snow on the ground in Caribou, Maine (NOAA 2019). The total snowfall during the season was more than 165 inches. During the same season, coastal Maine experienced 66 inches of snowfall.

Due to the changing climate, especially during winter months, coupled with the high frequency of lane departure crashes during these months, it is crucial to better understand how different weather variables impact lane departure crashes in Maine. We use a Negative binomial (NB) model with panel data and Generalized Estimating Equations (GEE) to analyze how monthly weather variables affect the frequency of lane departure crashes on rural Maine roads during the winter and non-winter periods from 2015 to 2019. This information provides a better understanding of how different weather factors influence lane departure crashes on different roadway facilities and jurisdictions leading to improved maintenance strategies, countermeasures, safety, and awareness.

Background: Crash frequency

A common theme in transportation safety research is that crash frequency is strongly correlated with traffic volume: the more vehicles that are on the road, the more likely a crash will occur. Many researchers have tried to quantify how much traffic volume is affected by adverse weather conditions. Maze et al. (2006a) found traffic volume during rain events decreased by less than 5% and during snow events the reduction varied from 7–80% (Maze, Agarwal, and Burchett 2006). In a combined review of literature that documents how adverse weather impacts crashes, Qui and Nixon (Qiu and Nixon, 2008) found a range from 1.35-3.45% reduction in traffic volume during rain events and a 7-56% decrease in traffic volume during snow events. In terms of safety and speed, Maze et al. found a 4-13% decrease in operation speed due to snow, and a 2-6% decrease due to rain (Maze, Agarwal, and Burchett 2006). In a cumulative review, Strong et al. (2010) found a range of 3-42% reduction in operation speed during snow events (Strong, Ye, and Shi 2010). they also found that storm type, intensity, and duration impact speed and traffic volume; stronger storms impact both speed and volume more than less severe storms.

Road surface conditions impact driving conditions differently, especially in locations with frequent inclement weather conditions such as those experienced in Maine. In Finland, Kilpelanien and

Summala (2007) surveyed drivers during 16 snow events during the winter of 2001–2002 (Kilpeläinen and Summala 2007). When comparing the perceived road condition to the Road Weather Information System (RWIS), 4.3% of drivers answered conditions were worse than posted, 73.4% answered the conditions were same, and 22.3% of drivers answered that the conditions were better than the RWIS values. The authors concluded that the drivers believe that if the road is just a little slippery, it is in good condition, perhaps due to how often Finnish drivers drive on weather impacted roadways. Road Surface Index (RSI) is a direct result from the weather that is occurring or had occurred during or before the time of a crash. Usman et al. (2010, 2012) analyzed crash frequency during snowstorm events in Ontario, Canada, observing at individual storm events (Usman, Fu, and Miranda-Moreno 2012; 2010). The researchers modeled the relationships between RSI, crash, and roadway characteristics. The 2010 research concluded that a 1% improvement in RSI from the mean resulted in a 2.28% decrease in the mean crashes where the 2012 study concluded in a 2% decrease.

All reviewed studies conclude that the presence of snow causes higher risk or frequency of crashes due to poorer road conditions and decreased visibility. Additionally, the existing research shows that the risk is highest during the first snowstorms of the winter season. For example, Andrey et al. (2003) found that the relative crash risk ratio during the first three snowfalls of the season was averaged to be 4.39 when drivers are not used to driving in slippery conditions (Andrey et al. 2003). Andrey et al. (2003) evaluated crash risk during adverse weather for six mid-sized Canadian cities that vary in climate. The analysis used crash data during 6-hr snow events and compared them to normal condition crashes, where they found relative risk to be 2.54. Andrey (2010) explored the long-term crash risk due to weather conditions in 10 Canadian cities (Andrey 2010). In this study the average relative risk of snowfall was found to be 1.87 though results from the 10 cities ranged from 1.66-2.17. The storms were separated by total accumulation and found crash risk increased for low and medium accumulation storms (i.e.: greater than 10 cm) and decreased for high intensity storms. Usman et al. (2012) show that a 1% increase in snowstorm intensity from the mean results in a 0.02% increase in mean crash counts (Usman, Fu, and Miranda-Moreno 2012). Strong et al. (2010) presented crash rates increasing due to snow ranging between 30–250% (Strong, Ye, and Shi 2010) higher than normal conditions . Qui and Nixon (2008) conclude that snow increases crash rates by up to 84% . Maze and colleagues (2006) concluded that severe winter storms can put drivers at 25 times higher risk of getting into a crash, and that drivers during moderately severe storms are 13 times more at risk.

The impact of precipitation in the form of rain on roadway crashes is shown to be less than snow. Andrey et al. (2003) determined an average crash risk during rain events to be 1.65, compared to the 2.54 found in the same study for snow events. Andrey (2010) found that from 1984–2002, the relative crash risk during rain events went from 1.9 to 1.5, which shows a significant decrease accredited to roadway and vehicle improvements (such as traction control) over the study period. When it comes to precipitation, some research has determined that precipitation does not affect or may improve crash risk or frequency. Zhao et al. (2019) looked at monthly weather variations and crashes in Connecticut and found that precipitation and crash frequency are negatively correlated. Qui and Nixon (2008) concluded that rain increased crash rates by up to 71%.

Other weather variables that have also been reported in studies include visibility, and wind. A 1% increase in visibility from the mean would result in a 0.5% decrease in mean crash frequency, and a 1% increase in wind speed from the mean would result in a 0.08% increase in mean crash frequency (Usman, Fu, and Miranda-Moreno 2012). Zhao and colleagues found that visibility effects in the form of heavy fog days were related to higher monthly crash frequencies; however, wind speed was found to have a negative association with monthly crash frequencies (Zhao et al. 2019).

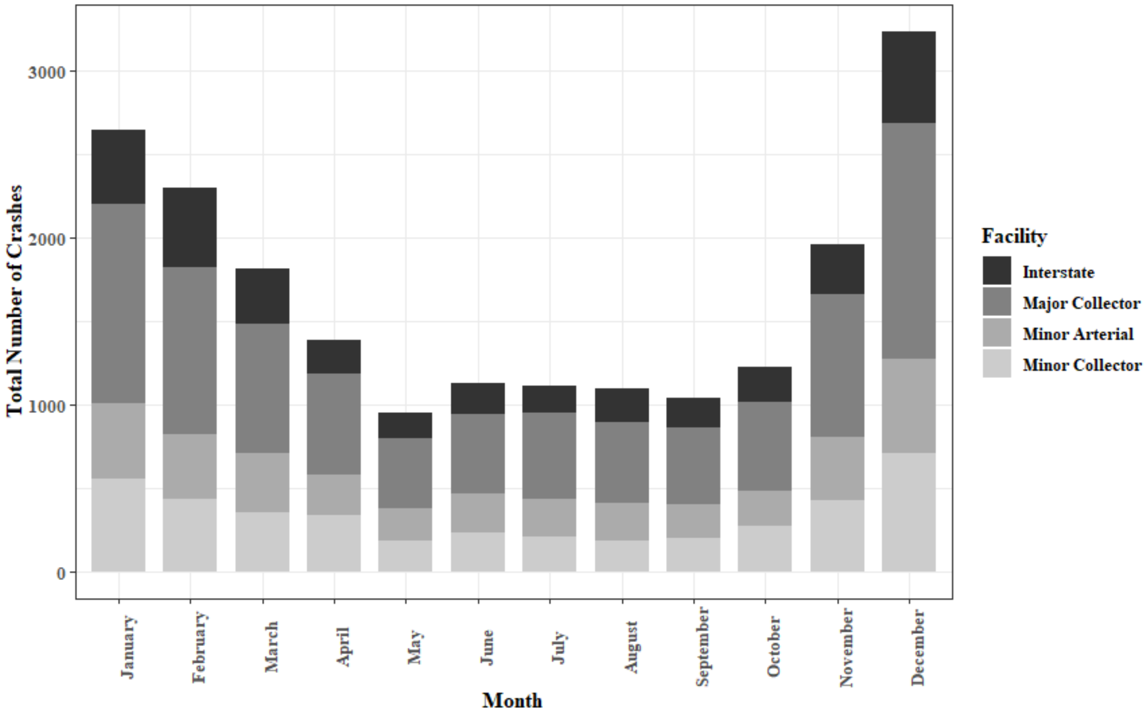
A trend in the literature includes issues on how and where weather data are collected. Most weather data are collected from national or airport weather stations, rather than local stations. In many studies, there is a significant impact in uncertainty due to a weather station location from a crash. Due to Maine's size and geographic diversity, this uncertainty could be a concern. In coastal regions of Maine, just 20–30 miles from another weather station, snow accumulations vary for storm events and total season accumulation, by 4 to 8 inches and 10 to 20 inches, respectively (Marquis et al. 2009). To accurately observe how crashes are influenced by weather factors, it is important to have accurate and reliable data; yet this is a limitation for most related research and discussed throughout most of the studies in literature.

In short, from reviewing research studies, it is apparent that weather factors impact traffic safety substantially. Yet, the impact varies from one jurisdiction to another. As noted earlier, given the unique location, weather, and terrain of Maine, it is important to gain a better understanding of how weather factors impact roadway safety in Maine, and similar locations including all states in New England region in the U.S., the Atlantic provinces of Canada, and other locations that have similar geographic, weather or infrastructure characteristics to make necessary changes and improvements to make roadways safer.

Data on frequency of roadway crashes

We collected, combined, and reduced the roadway network (roadway segments) and historical crash data from 2015 to 2019 and created uniform datasets for analysis. We analyzed four facilities: interstates, minor arterials, major collectors, and minor collectors. Since more than 80% of all roadways in Maine are rural, only rural roadways were considered for this study. To isolate the impact of weather factors on monthly lane departure crashes, winter and non-winter period datasets were created and used in modeling. For each segment, we aggregated crash data in each month and recorded as a monthly crash observation. Therefore, in total, each segment has 60 observations in five years. As discussed, over 64% of all lane departure crashes in Maine occur during the winter period. The total observed lane departure crashes by each facility type are visually presented in Figure 37.

Figure 37: Total Monthly Lane Departure Crashes for Each Facility Type.



We considered the monthly average daily traffic (MADT) rather than the annual value in our analysis to account for monthly variations of traffic volume due to events such as seasonal tourism. The summary statistics for crashes, roadway geometry, and MADT for all four facilities are presented in Table 21. All interstate segments in the study were divided roadways; all other analyzed facilities (minor arterials, major collectors, and minor collectors) were undivided two-lane roadways. The segments used in this analysis include segments with geometric characteristics that remained consistent (or unchanged) over the five-year analysis period.

Table 24: Summary Statistics of Exposure, Geometry, and Crashes in Different Facility Types

Variables	Interstates				Minor Arterials				Major Collectors				Minor Collectors			
	Mean	S.D.	Max.	Min	Mean	S.D.	Max.	Min	Mean	S.D.	Max.	Min	Mean	S.D.	Max.	Min
Total Crashes (5-years)	2.63	4.08	44.00	0.00	0.50	1.02	13.00	0.00	0.33	0.80	22.00	0.00	0.24	0.64	11.00	0.00
Segment Length (mile)	0.49	0.60	4.88	0.01	0.12	0.15	2.253	0.01	0.12	0.15	2.442	0.01	0.12	0.14	3.91	0.01
Lane Width (feet)	12.04	0.72	24.00	9.33	11.25	1.19	22.00	8.00	10.41	1.30	30.00	8.00	10.13	1.20	25.00	8.00
Number of Lanes	2.14	0.35	3.00	2.00	2.00	0.00	2.00	2.00	2.00	0.00	2.00	2.00	2.00	0.00	2.00	2.00
Speed Limit (mph)	68.31	6.74	75.00	25.00	45.17	9.71	55.00	25.00	43.18	8.06	55.00	20.00	41.81	5.85	50.00	20.00
Median (Present=1, not present=0)	1.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Left Shoulder Width (feet)	7.18	3.43	40.00	1.00	5.65	2.33	26.00	0.00	3.93	2.08	20.00	0.00	2.96	1.54	16.00	0.00
Right Shoulder Width (feet)	7.16	3.25	40.00	4.00	5.78	2.40	26.00	0.00	3.98	2.14	24.00	0.00	2.97	1.54	18.00	0.00
Travel Lane (Paved=1, not paved==0)	1.00	0.00	1.00	1.00	0.99	0.03	1.00	0.00	0.99	0.03	1.00	0.00	0.99	0.04	1.00	0.00
Left Shoulder (paved=1, not paved=0)	1.00	0.00	1.00	1.00	0.87	0.34	1.00	0.00	0.42	0.49	1.00	0.00	0.07	0.26	1.00	0.00
Right Shoulder (paved=1, not paved=0)	1.00	0.00	1.00	1.00	0.87	0.34	1.00	0.00	0.43	0.49	1.00	0.00	0.07	0.25	1.00	0.00
Curve Present (present=1, not present=0)	0.30	0.46	1.00	0.00	0.47	0.50	1.00	0.00	0.51	0.50	1.00	0.00	0.53	0.50	1.00	0.00
AADT (5 years)	12,668	9,536	41,190	230	5,164	3,241	20,983	357	2,125	1,809	16,950	32	1,134	972	16,447	29
January MADT	10,134	7,477	33,467	178	4,630	2,941	20,039	341	1,840	1,607	16,187	26	998	889	13,363	24
February MADT	9,929	7,160	33,261	185	4,557	2,905	19,881	338	1,821	1,589	16,060	26	982	882	13,281	23
March MADT	10,622	7,747	35,526	188	4,832	3,082	20,983	357	1,930	1,686	16,950	28	1,043	933	14,186	25
April MADT	11,764	8,629	38,224	210	5,181	3,340	22,284	379	2,085	1,816	18,001	30	1,120	993	15,263	27
May MADT	13,117	9,803	43,250	234	5,705	3,690	23,921	407	2,326	2,011	19,323	34	1,242	1,081	17,269	30
June MADT	14,222	10,837	46,442	250	5,987	3,908	24,235	412	2,461	2,133	19,577	36	1,305	1,118	18,544	33
July MADT	15,852	12,501	51,076	270	6,356	4,192	25,232	421	2,654	2,301	20,001	40	1,399	1,181	20,394	36
August MADT	16,004	12,541	51,282	276	6,292	4,133	24,570	418	2,638	2,279	19,832	40	1,393	1,174	20,477	36
September MADT	13,942	10,511	46,298	242	5,924	3,848	24,047	409	2,430	2,105	19,425	36	1,290	1,109	18,486	33
October MADT	13,055	9,603	43,250	232	5,624	3,617	23,344	397	2,285	1,978	18,857	34	1,219	1,062	17,269	30
November MADT	12,318	8,960	40,366	229	5,291	3,358	22,662	386	2,137	1,846	18,306	31	1,152	1,018	16,118	28
December MADT	11,376	8,444	36,659	200	4,958	3,132	21,277	362	1,979	1,718	17,187	28	1,068	950	14,638	26

We obtained weather data from the National Oceanic and Atmospheric Administration (NOAA) through their online resource (NOAA 2021). Accurate representation of weather data is necessary to ensure accuracy of the analysis. We compiled daily and monthly weather data from 16 weather stations throughout the state. We used two periods in the analyses. The winter period spans from November to April and the non-winter period from May to October. The summary statistics for weather variables for each period are presented in Table 25. Winter variables including snow or freezing temperatures are not applicable during the non-winter period. The maximum precipitation and maximum snowfall indicate the maximum 24-hr (12:00am—11:59pm) accumulation. Multiple variables related to snowfall were considered in modeling, including but not limited to maximum snowfall, total snowfall, the number of days in a month with snowfall accumulations, and the number of days in a month with more than 1-inch of snowfall [note: this variable considers snow events that can last several days, which is common in Maine].

Table 25: Summary Statistics for Monthly Weather Factors

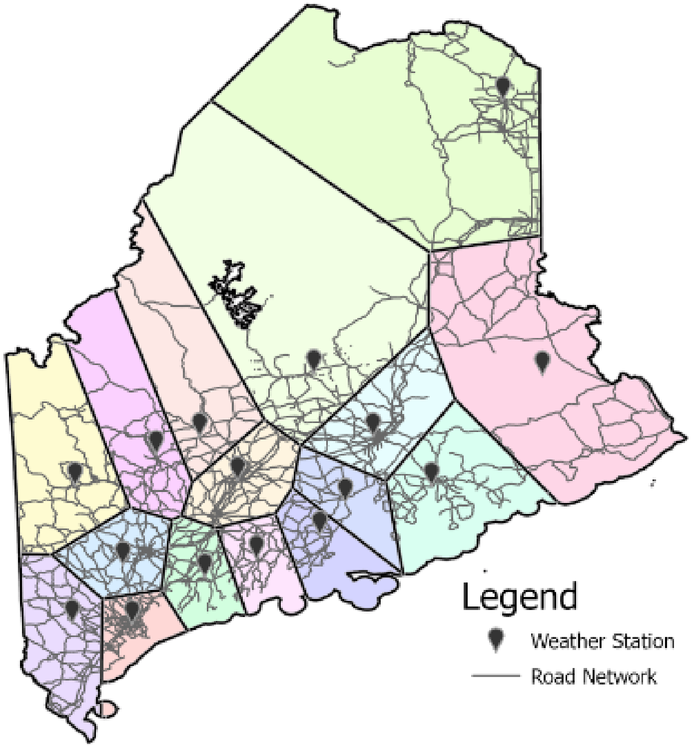
Variables	**Winter Period**						**Non-Winter Period**					
	Nov.	**Dec.**	**Jan.**	**Feb.**	**March**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**
	Mean (std.)	Mean (std.)	Mean (std.)	Mean (std.)	Mean (std.)	Mean (std.)	Mean (std.)	Mean (std.)	Mean (std.)	Mean (std.)	Mean (std.)	Mean (std.)
Max. Temperature (° F)	44.15 (4.35)	33.69 (4.75)	29.23 (3.77)	30.88 (6.66)	37.74 (3.31)	51.07 (2.42)	64.72 (4.29)	71.87 (2.23)	79.41 (2.23)	78.73 (1.76)	72.40 (2.56)	64.72 (4.29)
Average Temperature (° F)	35.58 (3.72)	25.16 (5.37)	19.76 (4.74)	20.34 (7.34)	28.04 (4.13)	41.09 (2.39)	53.82 (2.83)	61.25 (1.59)	68.61 (1.89)	67.86 (2.07)	61.33 (2.48)	53.82 (2.83)
Min. Temperature (° F)	27.05 (3.49)	16.64 (6.20)	10.28 (5.91)	28.04 (8.21)	18.36 (5.35)	31.11 (2.96)	42.91 (2.25)	50.62 (1.94)	57.82 (2.22)	57.00 (2.97)	50.26 (3.04)	42.91 (2.25)
Days with Max Temp ≤ 32° F	3.13 (3.32)	13.65 (5.57)	18.21 (5.40)	15.43 (6.54	8.15 (3.90)	0.74 (0.91)	NA[1]	NA	NA	NA	NA	NA
Max Precipitation (inch)	1.18 (0.41)	1.41 (0.58)	1.63 (0.62)	1.02 (0.44)	0.99 (0.41)	1.28 (0.51)	0.87 (0.49)	1.28 (0.50)	0.90 (0.44)	1.22 (0.49)	1.31 (1.12)	0.87 (0.49)
Total Monthly Precipitation (inch)	4.26 (2.04)	4.61 (1.24)	4.27 (1.34)	3.48 (1.28)	2.80 (1.00)	4.20 (1.38)	3.15 (1.83)	4.47 (1.55)	2.76 (1.11)	3.50 (1.33)	3.07 (1.69)	3.15 (1.83)
Days with Precipitation ≥ 0.1 inch	11.99 (3.31)	12.64 (3.14)	10.81 (2.70)	11.85 (2.13)	10.15 (2.37)	14.19 (3.40)	12.35 (4.20)	13.34 (2.64)	10.55 (2.36)	10.59 (2.28)	9.00 (2.21)	12.35 (4.20)
Days with Precipitation ≥ 1.0 inch	7.81 (3.20)	8.54 (2.42)	7.13 (2.35)	7.81 (1.96)	6.28 (2.19)	8.95 (2.61)	7.66 (3.39)	8.06 (2.25)	6.14 (1.84)	6.53 (1.97)	4.86 (1.54)	7.66 (3.39)
Max. Snowfall (inch)	2.18 (2.60)	6.83 (3.92)	8.67 (4.96)	9.37 (4.24)	8.46 (5.58)	3.06 (1.99)	NA	NA	NA	NA	NA	NA
Total Monthly Snowfall (inch)	5.24 (7.42)	16.98 (9.79)	21.81 (12.52)	26.65 (12.14)	15.97 (10.58)	4.61 (3.28)	NA	NA	NA	NA	NA	NA
Days with Snowfall ≥ 1.0 inch	1.66 (2.13)	4.36 (2.00)	5.33 (2.52)	6.31 (2.13)	3.29 (1.67)	1.50 (1.06)	NA	NA	NA	NA	NA	NA

[1] Not Applicable

Theisen polygons

The 16 weather stations used this study are scattered throughout the state, with one located in each of the 16 Maine counties. As noted in the literature review, most studies experienced limitations due to weather station locations or missing data. This was also a problem in this study. More weather stations could produce more accurate data for each roadway segment. With lack of data, assigning the weather-station data to each roadway segment becomes significantly important. We created Theisen polygons to minimize the spatial differences in matching the monthly weather variables to the road segments. Thiessen polygons are polygons that are created around individual data points that ensures only one data point (in this case weather station) is located in each polygon. The area within the polygon is assumed to have the weather observations of the associated station. Using ArcGIS Pro, each segment that falls inside of each polygon was assigned the corresponding weather station (Esri 2020). Figure 38 shows the polygons used in this study.

Figure 38: Thiessen Polygons Determined by Weather Station Locations



Methodology: Crash Frequency Model

The geometric characteristics of the segments remain constant from month to month while weather factors and MADT change. This will result in a panel (longitudinal) data. We used a negative binomial (or Poisson-gamma) and the Generalized Estimating Equation (GEE) approach to fit the models. The following equation indicates the general form of Negative binomial model (Hilbe 2011).

$$f(\mathrm{y_i}; \mu_\mathrm{i}, \alpha) = \frac{\Gamma\big((1/\alpha) + \mathrm{y_i}\big)}{\Gamma(1/\alpha)\Gamma(\mathrm{y_i} + 1)} \left(\frac{1}{1 + \alpha\mu_\mathrm{i}}\right)^{\frac{1}{\alpha}} \left(\frac{\alpha\mu_\mathrm{i}}{1 + \alpha\mu_\mathrm{i}}\right)^{\mathrm{y_i}}$$

where $\mathrm{y_i}$ is crash observation at site “i", μ_i is the mean response variable at site “i" and α is the over dispersion parameter. We assumed a log-linear function between the mean response variables and covariates ($\mathrm{x_{ik}}$) as: $\log(\mu_\mathrm{i}) = \beta_0 + \sum_{\mathrm{k}=1}^{\mathrm{m}} \beta_\mathrm{k}\mathrm{x_{ik}}$

where βs show the regression coefficients. Once the NB models were developed, the marginal effects at the mean were calculated for each variable. The analysis used the estimated coefficients and the average value of all variables, to predict the effect that 1% change of the respective variable would have on the average total monthly crashes. The expression for marginal effects for continuous variables is described as follows, where the β values are estimated by the NB model (Hilbe 2011).

$$\frac{\partial \mathrm{E}(\mathrm{y_i}|\mathrm{x_i})}{\partial \mathrm{x_{ik}}} = \mathrm{E}(\mathrm{y_i}|\mathrm{x_i})\beta_\mathrm{k} = \mathrm{EXP}(\mathrm{x}'\beta_\mathrm{k})\beta_\mathrm{k}$$

The expression for marginal effects (discrete change) for binary variables is described as follows.

$$\frac{\Delta\mathrm{Pr}(\mathrm{y_i}|(\mathrm{x_i} = 1|\mathrm{x_i} = 0))}{\Delta\mathrm{x_k}}$$

Modeling Results for Crash Frequency

Eight NB models were estimated. We considered segment length as an offset. The developed models covered two seasonal periods and four rural facility types (i.e., interstates, minor arterials, major collectors, and minor collectors.) Two seasonal groups of months were modeled separately to estimate the effects of the weather variables in different periods (i.e., winter vs. non-winter). The use of seasonal groups rather than one total model helped limit the amount of heterogeneity in the model and creating more accurate results for each seasonal period. The impact of winter weather variables would be depreciated if seasonal periods were not separated as snow and below freezing temperatures are not present during the non-winter period.

Since some geometric characteristic variables for some facility types are constant across the dataset, they were not included in the model. For example, the median was excluded from the model for all interstate segments, as interstates are always divided; the median was excluded for other facility types because they are almost always undivided. Travel lane pavement type was also excluded from the models, due to over 99% of all pavements being flexible pavement (e.g., asphalt) and only less than 1% being gravel or rigid. The number of lanes was excluded for minor arterials, major collectors, and minor collectors given that almost all roads are two lanes (therefore, we excluded roads that were not two lanes). For interstate models, left and right shoulder type was the same for all segments (due to design requirement, they are all paved) and were excluded from the interstate models.

Each model included traffic volume, geometric characteristics, and weather variables. The modeling results are presented in Tables 26-29. The tables also include Quasi-Likelihood Under the Independence Model Information Criterion (QIC), Root Mean Square Error (RMSE), Mean Square Prediction Error (MSPE), and Mean Absolute Error (MAE) to analyze goodness of fit (GOF). The empty cells on the tables show the insignificant or non-applicable variables.

Table 26: Modeling Results for Interstates

Variables	**Winter Period[1]**		**Non-Winter Period[1]**	
	Estimate	**Std.**	**Estimate**	**Std.**
Intercept	-10.320	1.280	-12.435	2.037
Ln (MADT)	0.676	0.057	0.642	0.084
Number of Lanes	-0.184	0.113	-	-
Speed Limit	0.061	0.011	0.090	0.018
Left Shoulder Width	-0.181	0.047	-0.230	0.054
Right Shoulder Width	-0.184	0.047	-0.220	0.054
Curve Present	-0.212	0.079	-0.168[3]	0.099
Max. Precipitation	-[2]	-	0.089	0.035
Days with Precipitation ≥1.0 (in)	0.022	0.009	0.027	0.012
Days with Snowfall ≥ 1.0	0.119	0.008	-	-
Dispersion Parameter (α)	1.134	0.147	0.849	0.271
QIC	16,444		9,204	
RSME	2.723		3.471	
MSPE	7.415		12.049	
MAE	2.624		3.382	

[1]Winter period is from November-April and non-winter period is from May-October.

[2]The empty cells show that variable is not statistically significant to the respective model or not applicable.

[3]Variable statistically significant at 90% otherwise significant at 95%.

Table 27: Modeling Results for Minor Arterial

Variables	**Winter Period[1]**		**Non-Winter Period[1]**	
	Estimate	**Std.**	**Estimate**	**Std.**
Intercept	-9.721	0.434	-11.262	0.592
Ln (MADT)	0.526	0.045	0.606	0.055
Lane Width	-[2]	-	0.067	0.030
Speed Limit	0.036	0.003	0.028	0.004
Left Shoulder Width	-0.071	0.012	-	-
Right Shoulder Width	-	-	-0.070	0.015
Right Shoulder Type	-	-	0.213	0.112
Curve Present	0.135	0.053	0.234	0.065
Days with Precipitation ≥1.0 (in)	0.025	0.008	-	-
Days with Snowfall ≥ 1.0	0.061	0.008	-	-
Dispersion Parameter (α)	1.661	0.355	1.029	0.569
QIC	26,162		15,890	
RSME	3.684		4.237	
MSPE	13.569		17.954	
MAE	3.656		4.212	

[1]Winter period is from November-April and non-winter period is from May-October.

[2]The empty cells show that variable is not statistically significant to the respective model or not applicable)

Table 28: Modeling Results for Major Collectors

	Winter Period[1]		Non-Winter Period[1]	
Variables	**Estimate**	**Std.**	**Estimate**	**Std.**
Intercept	-12.214	0.230	-11.269	0.283
Ln (MADT)	0.854	0.024	0.723	0.029
Speed Limit	0.038	0.002	0.030	0.003
Left Shoulder Width	-0.033	0.016	-[2]	-
Right Shoulder Width	-0.046	0.016	-0.083	0.011
Left Shoulder Type	-0.247	0.081	-	-
Right Shoulder Type	-0.164	0.082	-0.119	0.045
Curve Present	0.181	0.033	0.261	0.042
Total Precipitation (in.)	-	-	0.016	0.010
Max. Precipitation (in.)	0.136	0.025	-	-
Days with Precipitation ≥1.0 (in)	0.015	0.005	-	-
Days with Snowfall ≥ 1.0	0.078	0.005	-	-
Dispersion Parameter (α)	1.953	0.246	1.030	0.469
QIC	66,275		37,548	
RSME	4.266		4.793	
MSPE	18.198		22.970	
MAE	4.206		4.754	

[1] Winter period is from November-April and non-winter period is from May-October.

[2] The empty cells show that the variable is not statistically significant to the respective model or not applicable.

Table 29: Modeling Results for Minor Collectors

	Winter Period[1]		Non-Winter Period[1]	
Variables	**Estimate**	**Std.**	**Estimate**	**Std.**
Intercept	-13.000	0.348	-10.200	0.392
Ln (MADT)	0.878	0.032	0.621	0.040
Lane Width	0.044	0.021	-	-
Speed Limit	0.036	0.005	0.020	0.006
Left Shoulder Width	-0.030	0.015	-	-
Right Shoulder Width	-[2]	-	-0.036[3]	0.020
Left Shoulder Type	-0.359	0.153	-0.367	0.139
Right Shoulder Type	-0.488	0.156	-	-
Curve Present	0.153	0.047	0.364	0.063
Max. Precipitation	0.192	0.034	-	-
Days with Precipitation ≥1.0 (in)	0.040	0.008	-	-
Days with Snowfall ≥ 1.0	0.076	0.007	-	-
Dispersion Parameter (α)	1.791	0.422	2.595	1.184
QIC	34,252		17,912	
RSME	4.540		5.088	
MSPE	20.613		25.885	
MAE	4.473		5.059	

[1] Winter period is from November-April and non-winter period is from May-October.

[2] The empty cells show that the variable is not statistically significant to the respective model or not applicable.

[3] Variable statistically significant at 90% otherwise significant at 95%.

Traffic volume was modeled as a natural log of the monthly average daily traffic (MADT). As expected, MADT is positively correlated with the monthly crashes; as MADT increases, the number of crashes increases as well. This is the case for all four facilities and for both winter and non-winter periods. When comparing the two seasonal periods, MADT impacts interstate crashes similarly for both periods; for major and minor collectors, MADT impacts the number of crashes more during winter periods, likely because these facilities are not high priority for winter maintenance compared to interstates.

For all facilities, during both winter and non-winter periods, posted speed limit is positively correlated with monthly crashes; as the posted speed limit increases, the number of monthly lane departure crashes increases. The width of the left and right shoulders (whenever significant) showed a negative correlation with monthly crashes for all facilities for both seasonal periods. In Maine snow is plowed throughout the winter and left on the shoulder, accumulating with each storm (unless located in a hazardous location such as on bridges). This may explain why the impact of shoulder width on crashes is larger during the non-winter period compared to the winter periods. The results show that the paved shoulder can reduce number of crashes during winter session. The type of shoulder pavement is not significant in the non-winter period. For interstates, the modeling results show counterintuitive results for the curve present variable. Note that this variable only considers the presence of the curve on the segment, and not the in-depth characteristics or dimensions of the curve. Therefore, the counterintuitive sign can be due to the high design standards for majority of curves on interstates (most curves are smooth). In addition, drivers are more cautious when negotiating a curve on interstates. For all other facilities, the presence of curves is positively correlated with monthly crashes.

All 11 weather variables described in Table 25 were considered in modeling. Many of these variables, however, are correlated with each other (e.g., snow and freezing temperatures). We chose the best variables for modeling after careful investigations of their correlations and accounting for test of significance and GOFs. For winter period models, the temperature variable was correlated with other weather variables; yet it did not increase the goodness of fit, significance, or precision of coefficients as much as other weather variables. Hence, for winter period, we did not include this variable in the model. For non-winter periods, maximum temperature was included in models; we found a negative correlation between maximum temperature in month and monthly crashes for major and minor collectors during non-winter period.

Snow is one of the most important weather variables that impact roadway safety in Maine. Hence, finding the best variable to account for snowfall was important. After exploring many alternatives, we used the following variables for consideration: maximum monthly snowfall, total monthly snowfall, and the number of days in a month that received at least 1 inch of snow. We found that the number of days in a month that received at least 1 inch of snowfall provides the best statistical fit. The modeling results show that this variable has a positive correlation with winter month crashes for all four roadway types. We also considered multiple precipitation variables in modeling. For winter period, we found that days with precipitation greater 1-inch variable has a positive correlation with lane departure crashes for all facility types. This variable is also significant for interstates during the non-winter period. For major and minor collectors, the maximum precipitation variable is also significant and has a positive correlation with number of lane departure crashes during the winter period. This variable is significant for interstates during non-winter period as well. The variable indicating total monthly precipitation was found significant for major collectors during the non-winter period.

Marginal effect analysis of crash severity

Once the models were developed, the estimated coefficients can be used to analyze the marginal effect of each variable for each model. The results of the marginal effect analysis are presented in Table 30. Marginal effects show by how much the mean number of monthly crashes would be expected to change if the variable is changed by 1% compared to the mean value (Hilbe 2011). Marginal effects are calculated based on the estimates from the models. Therefore, only variables that are significant in models (as shown in Tables 26–29) are included in the marginal effect analysis.

Table 30: Results of Marginal Effects Analysis

Variables	**Winter Period**				**Non-Winter Period**			
	Interstate	**Minor Arterial**	**Major Collector**	**Minor Collector**	**Interstate**	**Minor Arterial**	**Major Collector**	**Minor Collector**
MADT	2.812%	0.413%	0.403%	0.296%	1.253%	0.254%	0.181%	0.115%
Lane Width	Not Sig[1]	Not Sig	Not Sig	0.015%	Not Sig	0.028%	Not Sig	Not Sig
Number of Lanes	-0.765%	NA	NA	NA	Not Sig	NA	NA	NA
Speed Limit	0.254%	0.030%	0.018%	0.013%	0.176%	0.012%	0.008%	0.004%
Left Shoulder Width	-0.753%	-0.055%	-0.014%	-0.010%	-0.449%	Not Sig	Not Sig	Not Sig
Right Shoulder Width	-0.765%	Not Sig	-0.023%	Not Sig	-0.427%	-0.029%	-0.021%	-0.006%
Left Shoulder Type	NA[2]	Not Sig	-0.118%	-0.123%	NA	Not Sig	Not Sig	-0.071%
Right Shoulder Type	NA	Not Sig	-0.078%	-0.078%	NA	0.089%	-0.031%	Not Sig
Curve Present	-0.894%	0.102%	0.088%	0.053%	-0.336%	0.097%	0.066%	0.067%
Max Temperature	NA	NA	NA	NA	Not Sig	Not Sig	-0.001%	-0.002%
Max. Precipitation	Not Sig	Not Sig	0.064%	0.065%	0.172%	Not Sig	Not Sig	Not Sig
Days with Precipitation >= 1.0 (in)	0.092%	0.020%	0.007%	0.014%	0.053%	Not Sig	Not Sig	Not Sig
Days with Snowfall >= 1.0	0.495%	0.048%	0.037%	0.026%	NA	NA	NA	NA

[1] The variable is not statistically significant to the respective model.

[2] Not Applicable.

The marginal effects of MADT variables are larger during the winter periods compared to non-winter period. For interstates, 1% increase in the natural log of MADT from its average value would cause an expected increase of 2.89% in average number of monthly crashes during the winter period whereas this number is 1.25% during the non-winter period. For minor arterials, major collectors, and minor collectors, 1% increase in the mean of natural log of MADT respectively would result in an expected increase of 0.44% 0.38%, and 0.30% in average monthly crashes during the winter period, and increase of 0.25%, 0.19%, and 0.12% during the non-winter period.

Regarding the geometric characteristics, a few notable results should be discussed. For winter period models, lane width is significant only for minor collectors. The marginal effect analysis shows that 1% increase in mean of lane width would result in 0.02% increase in average monthly crashes. During the non-winter period, lane width is significant only for minor arterials. The marginal effect shows that 1% increase in lane width would result in 0.03% increase in average monthly crashes of minor arterials during non-winter period. The positive correlation between lane width and monthly crashes may be counterintuitive, however the increase could be due to increase of traffic speed on wider roadways on these facilities. For interstates, the marginal effect analysis showed that 1% increase in the number of lanes from the mean would result in 0.79% decrease in average monthly winter period crashes. The posted speed limit is a significant variable for all facilities. However, as expected, the marginal effect analysis shows that the impact of posted speed limit is higher during the winter period compared to the non-winter period. For interstates, 1% increase in posted speed limit would result in 0.26% and 0.18% increase in average monthly crashes during the winter and non-winter periods, respectively. The width of the left and right shoulders is negatively correlated with crashes. For interstates, as the mean of the right or left shoulder width increases by 1%, the average monthly crashes are expected to decrease by around 0.78% during the winter period and around 0.44% during the non-winter period.

Weather variables affect crashes during the winter period more than the non-winter period. As discussed, only precipitation and snowfall variables were used in the winter-period models, due to the correlations with temperature. For all facilities, the number of days in a month with more than 1 inch of precipitation, and the number of days with more than 1 inch of snowfall were significant. For both variables, the highest impact is observed on interstates. The analysis showed that as the number of days with more than 1 inch of precipitation increases by 1% from the mean, the expected monthly crashes increase by 0.09% on interstates, 0.02% on minor arterials, 0.01% on major collectors, and 0.01% on minor collectors. The analysis also showed that as the number of days with more than 1 inch of snowfall increases by 1% from the mean, the expected monthly crashes increase by 0.51% on interstates, 0.05% on minor arterials, 0.04% on major and 0.03% on minor collectors. In addition, as the maximum precipitation increases from the mean by 1%, the expected monthly crashes increase by approximately 0.06% and 0.07% during the winter period for major and minor collectors respectively.

For the non-winter period, precipitation variables are significant only for interstates and major collectors. For non-winter period, as the maximum daily precipitation increases from the mean by 1%, the average of monthly crashes increases by 0.17% on interstates. As the number of days in the month with more than 1 inch of precipitation increase by 1% the average monthly crashes increased by 0.05% for interstates. For non-winter period, as the total monthly precipitation increases from the mean by 1%, the average of monthly crashes increases by 0.004% for major collectors.

Summary: Crash Frequency Models

Lane departure crashes are the leading cause of roadway fatalities in Maine. The majority of these crashes happen during the winter period (November through April). This study analyzed the impact of weather variables on lane departure crashes on rural Maine roads for interstates, minor arterials, major collectors, and minor collectors. To appropriately estimate the impact of weather variables, we developed two separate models for two seasonal periods. We used monthly aggregated segment crashes along with monthly AADT, geometric characteristics, and weather factors in the model. The modeling results and marginal effects analysis indicate a significant difference between the coefficients of the models developed for winter and non-winter periods. We found that, during the winter period, the number of days that experienced at least 1 inch of snow or precipitation significantly impact the crash frequency. The marginal effect analysis shows that as the number of days with more than 1 inch of precipitation increases by 1% from the mean, the expected monthly crashes increase by 0.09% on interstates, 0.02% on minor arterials, 0.01% on major collectors and 0.01% on minor collectors. The marginal effect analysis also shows that as the number of days with more than 1 inch of snowfall increases by 1% from the mean, mean of crashes increase by 0.51% on interstates, 0.05% on minor arterials, 0.04% on major collectors, and 0.03% on minor collectors. During the non-winter period, interstate crashes are positively correlated with two variables, maximum precipitation and days with precipitation greater than 1 inch. During the non-winter period, major collector crashes are positively correlated with total monthly precipitation.

The primary goal of this analysis was to determine the impact of various weather factors on lane departure crashes. For all four facilities, the number of days in a month with more than 1 inch of precipitation or snowfall showed to positively associated with the frequency of crashes. Various countermeasures could help decrease crashes on these days, including use of signage, news reporting, and education to ensure drivers are aware of the danger on these days. In rainfall, the risk of hydroplaning, and in snowfalls, the risk of slippery conditions and driver error increases, which could result in higher crash frequencies. The state may consider reducing the adverse impact of these factors by imposing higher tire condition standards. Precipitation also alters visibility. Therefore, it is important to decrease driving speeds on high precipitation days through proper messaging. During the non-winter period, both interstates and major collectors showed increased crash frequency on days with maximum rainfall. Similar countermeasures as those stated earlier such as increased signage or enforcement to decrease speed should be considered. Finally, more safety education and awareness are recommended during the storm events.

In terms of geometric features that positively affect crashes, curve presence proved to increase crash frequency on minor arterials, major collectors, and minor collectors. Countermeasures that should be considered for these locations include increasing the signage to make drivers aware of the upcoming curves, reducing speed limits at these locations, as well as developing the infrastructure or roadway facility. Countermeasures to reduce lane departure crashes include the installation of rumble strips as well as the barriers and guardrails. This analysis only considered the presence of a curve as a variable in the models; however, more research is recommended to include more information about the curves such as radius, friction, or superelevation in the model to determine hotspots. Finally, higher speed limits were associated with higher crash frequencies, so speed limits in high-crash locations should be reevaluated to potentially reduce lane departure crashes at these locations.

It is also worth noting that our analysis considered two time periods, the winter period, from November to April, and the non-winter period from May to October. By separating these two periods, we indirectly accounted for the greater darkness during the winter period. It would be important to study the impact of time of day (or darkness) in frequency of lane departure crashes in future research.

Impact of Roadway, Driver, and Weather Factors on Severity of Lane Departure

To date, there is limited research exploring the contributing factors on lane departure crashes considering the combination of driver, roadway, and daily weather (rather than weather cited in crash reports). We hypothesize that the combination of discussed factors contributes to the severity of lane departure crashes, and the higher proportion of fatalities in Maine compared to other New England states. This study uses Multinomial Logistic Regression model to understand the impact of various roadway, driver, and weather factors on the severity of single-vehicle lane departure crashes that occurred in the three-year period from 2017 to 2019. Given the difference in roadway conditions as well as maintenance strategies, the analysis is divided based on four different facility types. These facilities are (1) principal arterials–interstates highways (referred to as interstates in this report), (2) minor arterials, (3) major collectors, and (4) minor collectors. The results of this study provide a better understanding of contributing factors (e.g., roadway, driver, and weather) on severity of lane departure crashes on different roadway facilities leading to improved management, maintenance, and safety.

Background

Multiple studies explored the impact of demographic variables on severity of crashes. Drivers above 65 years old have a 68% higher chance of getting into a severe or fatal crash in single-vehicle crashes in New Mexico (Wu et al. 2016). Drivers over 65 years old are 105% more likely to be in a fatal crash in California (Kim et al. 2013). A study in four south central states concluded that the likelihood of being in a severe crash is 38–43% lower for younger drivers (below the age of 25) (Li et al. 2019). When studying the effects of age and sex on single-vehicle crashes on adverse roadway conditions in Indiana, Morgan and Mannering found female drivers of all ages, and older males experience increased likelihood of severe injury resulting from adverse weather conditions (Morgan and Mannering 2011). They concluded that male drivers below the age of 45 are less likely to be in severe crashes resulting from adverse conditions compared to older drives. The study in California found that male drivers are 107% more likely of being in a fatal crash in California (Kim et al. 2013); however, the study by Li et al. found that male drivers are 6-17% less likely to be in fatal crashes (Li et al. 2019).

When occupants in vehicles are not wearing seatbelts, studies have showed crash severity increases. A study in Florida found that, in each location type, injury severity increases when drivers are not using seatbelts (Abdel-Aty 2003). Li et al. (2019) found severity increases by 265–318% when seatbelts were not worn. The study in California found that when seatbelts are worn, the chances of crashes resulting in fatalities decrease by 60% (Kim et al. 2013). When drivers exceed posted speed limits in California, crashes are 105% more likely to result in fatalities (Kim et al. 2013), and Abdel-Aty found that the increase in severity was present for all location types in Florida (Abdel-Aty 2003). Operating under the influence of drugs or alcohol is a common cause of accidents. Li et al. (2019) found that operating under the influence increases likelihood of severe and fatal crashes by 204–502%, Kim et al. (2013)found the increasing chance of fatality to be 73%.

In a review that studied impact of various weather factors on crashes, the authors concluded that there was an average increase of 9% in fatality rate during adverse weather conditions (Qiu and Nixon 2008a). A study on the effects of snowfall on crash severity in the contiguous 48 states, found that snow days increased nonfatal injury rates, and property-damage-only crashes (Eisenberg and Warner 2005). They also found that during the first snow day of the season, the fatality rate increased, as well as injury rates (Eisenberg and Warner 2005). This issue was found to be especially relevant for older drivers although the first snow days only accounted for 3% of the total snow days evaluated in the study (Eisenberg and Warner 2005). Li et al. found that when road conditions were wet, the probability of severe crashes decreased by about 40% in south central states (Li et al. 2019). Zhang et al. found that as minimum visibility decreased by one unit leads to an increase in 0.1% in the probability of non-injury crashes on freeways in China (Zhang et al. 2021). This indicates that lower visibility decreases the chances of severe crashes, perhaps due to increased caution. It was found that as wind speed increased by 1 unit there was a 0.9% decrease in severe and fatal crashes. In a study of occupant injury severity during winter weather, Shaheed et al. (2016) analyzed crashes in Iowa and considered interaction variables, one of which was road surface condition and temperature. They found that there is a 70% higher chance of serious injury than no injury on roadways that are dry when pavement temperature is above freezing (Shaheed et al. 2016). This is considered clear conditions, which indicate clear conditions result in more severe crashes. The study also found that when visibility was within 6 miles and surface condition was not dry (i.e., wet, snowy, etc.), the probability of occupants getting into a severe crash decreased by 45% (Shaheed et al. 2016). Another study found that during snow days fatalities were decreased by 16% (Eisenberg and Warner 2005).

The study by Li et al. found variables such as grade, curve, impaired driving, multiple lanes, and not using a seatbelt increases probability of severe crashes (Li et al. 2019). The variable of grade was found to increase severe injury during rain events by 50%. In a study using real-time weather data, studying crash severity on freeways in China, Zhang et al. found that a 1% increase in grade increases the probability of severe and fatal crashes by 2.86% (Zhang et al. 2021). Previous research found that there is an increase in crash severity by a range of 20–80% on curves (Li et al. 2019).

The review of previous studies shows that the impact of driver, roadway, and weather factors on severity of crashes varies from one jurisdiction to another. As discussed, Maine has aging infrastructures and the oldest population in the U.S., is the third coldest states in the U.S., and has the highest lane departure fatality rate in the New England region. Maine conditions are not comparable to other states and a unique case study to understand the impact of driver, roadway, and weather factors on severity of lane departure crashes is important.

Description of data

We collected crash data and contributing factors recorded in Maine and created a uniform dataset for each facility type—interstates, minor arterials, major collectors, and minor collectors. A total of 11,409 single-vehicle lane departure crashes were reported from 2017 to 2019 in Maine. The total crashes for interstates, minor arterials, major collectors, and minor collectors are 2,190, 1,994, 4,940, and 2,285, respectively. It is important that these facilities are analyzed separately due to the design, safety conditions, and differences in maintenance strategies (as described above). Four injury severity categories were considered for analysis: fatal-incapacitating injury crashes (KA), non-incapacitating injury (B), possible injury (C), and property damage only (PDO).

The contributing factors were classified in four major subcategories. First, the driver factors, which included subcategory variables such as driver age and sex as well as behavioral factors such as speeding, operating under the influence (OUI), and seat belt usage. Over 15 driver variables were considered, and eventually 7 variables were included in the analysis. The second subcategory included crash variables, such as time of day, crash type, day of the week, and vehicle type. In total 20 variables in this category were considered and eventually 4 variables were included in the analysis. The third subcategory included roadway characteristics, such as curve presence, posted speed limit, and lane width. Over 12 variables were considered, and eventually 3 variables were included in the analysis. The fourth subcategory included weather variables; a total of 7 weather variables were considered and eventually 4 variables were considered in the analysis.

The weather data was extracted from NOAA for the day of crash from 16 weather stations to allocate the weather variables to each crash record, we created Thiessen polygons around the 16 weather stations using ArcGIS Pro as described earlier in the Theisen polygons section (see Figure 38).

As noted above, many variables or combination of variables were considered, but not included in analysis (due to exploring correlation, significant test, and statistical fit). These variables include shoulder width, shoulder pavement, lighting condition, the presence of rumble strips, freezing temperatures, wind, and more. The categorical variables were also created based on extensive preliminary analyses. For example, for the driver age variable, we found that designating "young" to drivers under the age of 30, "middle" to drivers between 30 and 64, and older to drivers of 65 years or above is the best representation of age category for this study. As another example, the variable "time of day" was divided into peak and off-peak time after extensive investigations. The peak time is between 6:00AM–10:00AM and 3:00PM–7:00PM Monday-Friday; the off-peak is otherwise. The speed limit variable differentiates between roadways with posted speed limits above 70 mph on interstates, and above 45 mph on all other facilities. The time between dawn and dusk was considered as the nighttime variable. The seasonal period variable represents the winter period from November to April and the non-winter period from May to October. In this study, the surface conditions are considered as not dry if an officer noted the surface as wet, snow, slush, etc., and dry otherwise. This variable is not the same as weather variables as the surface condition may or may not be dry after storms. The variable snow day was used to describe if the area in which a crash occurred experienced at least 1 inch of snow accumulation on the day of the crash. The variable precipitation describes if there was any precipitation accumulation on the day the crash occurred. Tables 31–34 show the summary of data used for the analysis for interstates, minor arterial, major collectors, and minor collectors, respectively.

Table 31: Count and Frequency of Variables for the Interstate Facility

Variables		**PDO**		**C**		**B**		**KA**	
		Count	**Ratio**	**Count**	**Ratio**	**Count**	**Ratio**	**Count**	**Ratio**
Driver Age	Young	679	31.0%	138	6.3%	103	4.7%	23	1.1%
	Middle	735	33.6%	153	7.0%	148	6.8%	41	1.9%
	Older	100	4.6%	28	1.3%	27	1.2%	15	0.7%
Male Driver Indicator	Male	1,024	46.8%	183	8.4%	176	8.0%	58	2.6%
	Not Male	490	22.4%	136	6.2%	102	4.7%	21	1.0%
Driver License	Suspended	27	1.2%	10	0.5%	12	0.5%	7	0.3%
	Active	1,487	67.9%	309	14.1%	266	12.1%	72	3.3%
Sobriety	OUI	43	2.0%	8	0.4%	17	0.8%	15	0.7%
	not OUI	1,471	67.2%	311	14.2%	261	11.9%	64	2.9%
Distractions	Distracted	74	3.4%	24	1.1%	17	0.8%	8	0.4%
	Not Distracted	1,440	65.8%	295	13.5%	261	11.9%	71	3.2%
Driver Speed	Speeding	13	0.6%	3	0.1%	4	0.2%	3	0.1%
	Not Speeding	1,501	68.5%	316	14.4%	274	12.5%	76	3.5%
Seatbelt	Not Wearing	18	0.8%	21	1.0%	30	1.4%	22	1.0%
	Wearing	1,496	68.3%	298	13.6%	248	11.3%	57	2.6%
Crash Type	Rollover	23	1.1%	8	0.4%	15	0.7%	3	0.1%
	Not Rollover	1,491	68.1%	331	15.1%	263	12.0%	76	3.5%
Time of Day	Peak	648	29.6%	163	7.4%	109	5.0%	34	1.6%
	Non-Peak	866	39.5%	156	7.1%	169	7.7%	45	2.1%
Night-time	Night	696	31.8%	127	5.80%	117	5.3%	33	1.5%
	Not Night	818	37.4%	192	8.77%	161	7.4%	46	2.1%

Variables		PDO		C		B		KA	
		Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio
Speed Limit	>70 mph	1,509	68.9%	319	14.6%	278	12.7%	78	3.6%
	<70 mph	5	0.2%	0	0.0%	0	0.0%	1	0.0%
Curve	Present	323	14.7%	72	3.3%	63	2.9%	12	0.5%
	Not Present	1,191	54.4%	247	11.3%	215	9.8%	67	3.1%
Grade	Not Level	346	15.8%	97	4.4%	69	3.2%	18	0.8%
	Level	1,168	53.3%	222	10.1%	209	9.5%	61	2.8%
Season	Winter	1,103	50.4%	211	9.6%	166	7.6%	29	1.3%
	Non-Winter	411	18.8%	108	4.9%	112	5.1%	50	2.3%
Surface Condition	Not Dry	1,084	49.5%	212	9.7%	163	7.4%	23	1.1%
	Dry	430	19.6%	107	4.9%	115	5.3%	56	2.6%
Snow	> 1 inch	182	8.3%	40	1.8%	20	0.9%	1	0.0%
	< 1 inch	1,332	60.8%	279	12.7%	258	11.8%	78	3.6%
Temperature	> 60°F	1,166	53.2%	229	10.5%	188	8.6%	43	2.0%
	≤ 60°F	348	15.9%	90	4.1%	90	4.1%	36	1.6%
Precipitation	Present	488	22.3%	105	4.8%	82	3.7%	18	0.8%
	Not Present	1,026	46.8%	214	9.8%	196	8.9%	61	2.8%

Table 32: Count and Frequency of Variables for the Minor Arterial Facility

Variables		PDO		C		B		KA	
		Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio
Driver Age	Young	524	26.3%	164	8.2%	77	3.9%	24	1.2%
	Middle	652	32.7%	209	10.5%	88	4.4%	43	2.2%
	Older	124	6.2%	42	2.1%	38	1.9%	9	0.5%
Male Driver Indicator	Male	851	42.7%	250	12.5%	124	6.2%	53	2.7%
	Not Male	449	22.5%	165	8.3%	79	4.0%	23	1.2%
Driver License	Suspended	38	1.9%	20	1.0%	15	0.8%	8	0.4%
	Active	1,262	63.3%	395	19.8%	188	9.4%	68	3.4%
Sobriety	OUI	98	4.9%	55	2.8%	24	1.2%	20	1.0%
	Not OUI	1,202	60.3%	360	18.1%	179	9.0%	56	2.8%
Distractions	Distracted	130	6.5%	45	2.3%	24	1.2%	7	0.4%
	Not Distracted	1,170	58.7%	370	18.6%	179	9.0%	69	3.5%
Driver Speed	Speeding	20	1.0%	6	0.3%	1	0.1%	6	0.3%
	Not Speeding	1,280	64.2%	409	20.5%	202	10.1%	70	3.5%
Seatbelt	Not Wearing	49	2.5%	48	2.4%	35	1.8%	42	2.1%
	Wearing	1,251	62.7%	367	18.4%	168	8.4%	34	1.7%
Crash Type	Rollover	32	1.6%	19	1.0%	10	0.5%	5	0.3%
	Not Rollover	1,268	63.6%	396	19.9%	193	9.7%	71	3.6%
Time of Day	Peak	580	29.1%	162	8.1%	90	4.5%	36	1.8%
	Non-Peak	720	36.1%	253	12.7%	113	5.7%	40	2.0%
Night-time	Night	581	29.14%	179	8.98%	84	4.21%	35	1.76%
	Not Night	719	36.06%	236	11.84%	119	5.97%	41	2.06%
Speed Limit	> 45 mph	1,099	55.1%	365	18.3%	165	8.3%	64	3.2%
	< 45 mph	201	10.1%	50	2.5%	38	1.9%	12	0.6%
Curve	Present	608	30.5%	192	9.6%	110	5.5%	39	2.0%
	Not Present	693	34.8%	223	11.2%	93	4.7%	37	1.9%
Grade	Not Level	469	23.5%	141	7.1%	76	3.8%	19	1.0%
	Level	831	41.7%	274	13.7%	127	6.4%	57	2.9%
Season	Winter	953	47.8%	232	11.6%	94	4.7%	26	1.3%

	Non-Winter	347	17.4%	183	9.2%	109	5.5%	50	2.5%
Surface Condition	Not Dry	773	38.8%	184	9.2%	72	3.6%	15	0.8%
	Dry	527	26.4%	231	11.6%	131	6.6%	61	3.1%
Snow	> 1 inch	131	6.6%	14	0.7%	6	0.3%	2	0.1%
	< 1 inch	1,169	58.6%	401	20.1%	197	9.9%	74	3.7%
Temperature	> 60°F	1,018	51.1%	264	13.2%	116	5.8%	30	1.5%
	≤ 60°F	282	14.1%	151	7.6%	87	4.4%	46	2.3%
Precipitation	Present	348	17.5%	88	4.4%	41	2.1%	13	0.7%
	Not Present	952	47.7%	327	16.4%	162	8.1%	63	3.2%

Table 33: Count and Frequency of Variables for the Major Collector Facility

Variables		**PDO**		**C**		**B**		**KA**	
		Count	**Ratio**	**Count**	**Ratio**	**Count**	**Ratio**	**Count**	**Ratio**
Driver Age	Young	1,469	29.7%	436	8.8%	237	4.8%	78	1.6%
	Middle	1,448	29.3%	461	9.3%	247	5.0%	108	2.2%
	Older	241	4.9%	131	2.7%	51	1.0%	33	0.7%
Male Driver Indicator	Male	1,994	40.4%	572	11.6%	361	7.3%	151	3.1%
	Not Male	1,164	23.6%	456	9.2%	174	3.5%	68	1.4%
Driver License	Suspended	108	2.2%	46	0.9%	36	0.7%	20	0.4%
	Active	3,050	61.7%	982	19.9%	499	10.1%	199	4.0%
Sobriety	OUI	210	4.3%	117	2.4%	95	1.9%	62	1.3%
	Not OUI	2,948	59.7%	911	18.4%	440	8.9%	157	3.2%
Distractions	Distracted	244	4.9%	116	2.3%	58	1.2%	16	0.3%
	Not Distracted	2,914	59.0%	912	18.5%	477	9.7%	203	4.1%
Driver Speed	Speeding	56	1.1%	31	0.6%	20	0.4%	32	0.6%
	Not Speeding	3,102	62.8%	997	20.2%	515	10.4%	187	3.8%
Seatbelt	Not Wearing	132	2.7%	117	2.4%	107	2.2%	123	2.5%
	Wearing	3,026	61.3%	911	18.4%	428	8.7%	96	1.9%
Crash Type	Rollover	78	1.6%	55	1.1%	32	0.6%	14	0.3%
	Not Rollover	3,080	62.3%	973	19.7%	503	10.2%	205	4.1%
Time of Day	Peak	1,454	29.4%	427	8.6%	197	4.0%	79	1.6%
	Non-Peak	1,704	34.5%	601	12.2%	338	6.8%	140	2.8%
Night-time	Night	1378	27.89%	447	9.05%	248	5.02%	84	1.70%
	Not Night	1780	36.03%	581	11.76%	287	5.81%	135	2.73%
Speed Limit	> 45 mph	2,486	50.3%	834	16.9%	429	8.7%	189	3.8%
	< 45 mph	672	13.6%	194	3.9%	106	2.1%	30	0.6%
Curve	Present	1,635	33.1%	520	10.5%	306	6.2%	132	2.7%
	Not Present	1,523	30.8%	508	10.3%	229	4.6%	87	1.8%
Grade	Not Level	1,315	26.6%	418	8.5%	226	4.6%	86	1.7%
	Level	1,843	37.3%	610	12.3%	309	6.3%	133	2.7%
Season	Winter	2,339	47.3%	594	12.0%	293	5.9%	77	1.6%
	Non-Winter	819	16.6%	424	8.6%	242	4.9%	142	2.9%
Surface Condition	Not Dry	2,067	41.8%	532	10.8%	221	4.5%	64	1.3%
	Dry	1,091	22.1%	496	10.0%	314	6.4%	155	3.1%
Snow	> 1 inch	332	6.7%	63	1.3%	16	0.3%	2	0.0%
	< 1 inch	2,826	57.2%	965	19.5%	519	10.5%	217	4.4%
Temperature	> 60°F	2,485	50.3%	675	13.7%	338	6.8%	90	1.8%
	≤ 60°F	673	13.6%	353	7.1%	197	4.0%	129	2.6%
Precipitation	Present	2,339	47.3%	594	12.0%	293	5.9%	77	1.6%
	Not Present	819	16.6%	424	8.6%	242	4.9%	142	2.9%

Table 34: Count and Frequency of Variables for the Minor Collector Facility

Variables		PDO		C		B		KA	
		Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio
Driver Age	Young	762	33.3%	210	9.2%	109	4.8%	35	1.5%
	Middle	662	29.0%	188	8.2%	102	4.5%	42	1.8%
	Older	111	4.9%	32	1.4%	21	0.9%	11	0.5%
Male Driver Indicator	Male	949	41.5%	208	9.1%	141	6.2%	57	2.5%
	Not Male	586	25.6%	222	9.7%	91	4.0%	31	1.4%
Driver License	Suspended	48	2.1%	22	1.0%	11	0.5%	8	0.4%
	Active	1,487	65.1%	408	17.9%	221	9.7%	80	3.5%
Sobriety	OUI	84	3.7%	41	1.8%	45	2.0%	21	0.9%
	Not OUI	1,451	63.5%	389	17.0%	187	8.2%	67	2.9%
Distractions	Distracted	121	5.3%	40	1.8%	29	1.3%	7	0.3%
	Not Distracted	1,414	61.9%	390	17.1%	203	8.9%	81	3.5%
Driver Speed	Speeding	41	1.8%	25	1.1%	21	0.9%	11	0.5%
	Not Speeding	1,494	65.4%	405	17.7%	211	9.2%	77	3.4%
Seatbelt	Not Wearing	52	2.3%	59	2.6%	43	1.9%	37	1.6%
	Wearing	1,483	64.9%	371	16.2%	189	8.3%	51	2.2%
Crash Type	Rollover	45	2.0%	24	1.1%	12	0.5%	6	0.3%
	Not Rollover	1,490	65.2%	406	17.8%	220	9.6%	82	3.6%
Time of Day	Peak	705	30.9%	198	8.7%	103	4.5%	34	1.5%
	Non-Peak	830	36.3%	232	10.2%	129	5.6%	54	2.4%
Nighttime	Night	631	27.61%	183	8.01%	88	3.85%	35	1.53%
	Not Night	904	39.56%	247	10.81%	144	6.30%	53	2.32%
Speed Limit	> 45 mph	1,069	46.8%	313	13.7%	174	7.6%	72	3.2%
	< 45 mph	466	20.4%	117	5.1%	58	2.5%	16	0.7%
Curve	Present	870	38.1%	248	10.9%	128	5.6%	64	2.8%
	Not Present	665	29.1%	182	8.0%	104	4.6%	24	1.1%
Grade	Not Level	673	29.5%	209	9.1%	98	4.3%	37	1.6%
	Level	862	37.7%	221	9.7%	134	5.9%	51	2.2%
Season	Winter	1,161	50.8%	291	12.7%	127	5.6%	35	1.5%
	Non-Winter	374	16.4%	139	6.1%	105	4.6%	53	2.3%
Surface Condition	Not Dry	1,049	45.9%	239	10.5%	108	4.7%	27	1.2%
	Dry	486	21.3%	191	8.4%	124	5.4%	61	2.7%
Snow	> 1 inch	174	7.6%	23	1.0%	21	0.9%	1	0.0%
	< 1 inch	1,361	59.6%	407	17.8%	211	9.2%	87	3.8%
Temperature	> 60°F	1,244	54.4%	315	13.8%	143	6.3%	41	1.8%
	≤ 60°F	291	12.7%	115	5.0%	89	3.9%	47	2.1%
Precipitation	Present	407	17.8%	81	3.5%	52	2.3%	12	0.5%
	Not Present	1,128	49.4%	349	15.3%	180	7.9%	76	3.3%

Methodology: Crash severity

Crash severity is identified as one of the following five categories, property damage only (PDO), possible injury (C), non-incapacitating injury (B), incapacitating injury (A) and fatal (K) crash. For the analysis, we combined K and A crash outcomes. To model crash severity, we used a

Multinomial Logistics (MNL) model (Hilbe 2011; Shankar and Mannering 1996; Washington, Karlaftis, and Mannering 2011; Shirazi et al. 2017; Geedipally et al. 2019; Zhao et al. 2021).

Similar to some of the previous studies (see, Geedipally at al. 2019), the MNL model was found to be a more appropriate model compared to the mixed logit for the data in hand. When using the MNL model, one category is designated as the reference category, and all other categories are compared to the reference; in this study, the PDO severity outcome was considered as the reference category. The probability of the *ith* observation experiencing the *jth* output injury is defined as follows:

$$\mathrm{P_{ij}} = \frac{\mathrm{e}^{\mathrm{U_{ij}}}}{1 + \sum_{\mathrm{j}} \mathrm{e}^{\mathrm{U_{ij}}}}$$

where, p_{ij} is the probability of the occurrence of crash severity "*j*" for observation "*i*", and U_{ij} is the deterministic part of the crash type likelihood. A linear function is used to link the crash severity with the various contributing factors as follows:

$$\mathrm{U_{ij}} = \mathrm{\beta_{0j}} + \sum_{\mathrm{k}} \mathrm{\beta_{kj} X_{ik}}$$

where β_{0j} is the constant term for *jth* category, X_{ik} is the *kth* variable for the *ith* observation and β_{kj} is the coefficient for the *kth* variable *jth* crash type. The coefficients are estimated using the maximum likelihood approach. To interpret the, we also estimated the Odds Ratio (OR) (Rahman et al. 2021; Holdridge et al. 2005) and reported in results section.

Results: Crash Severity

A multinomial logit model was estimated for each facility type. The PDO severity outcome was used as the reference (or base) category in each model. Therefore, the modeling results and the corresponded odds ratios (OR) discussed in this section are compared to crashes the PDO crash outcome. Tables 35–38 show the modeling results (e.g., the estimated coefficient of significant variables), and the corresponding OR for interstate, minor arterials, major collectors, and minor collectors, respectively. The tables also include the Akaike Information Criterion (AIC), Log-Likelihood, and McFadden's R^2 to analyze the goodness of fit.

Interstate facilities crash severity

Table 35 shows the modeling results for rural interstate roadways in Maine. The young driver category (younger than 29) was used as the reference group. The results show a positive correlation between the age of middle and older drivers and the Level B and Level KA severity outcomes. Given a crash, the odds of Level B and Level KA severity outcomes compared to PDO increases by 39% and 83%, respectively, for middle-aged drivers compared to young drivers. For older drivers, the results show that the odds of Level B and Level KA severity outcomes compared to PDO increases by 72% and more than 327%, respectively, compared to young drivers. The modeling results show that the odds a crash leading to a Level C or Level B severity outcome compared to PDO is respectively 38% and 30% smaller for male drivers. The results indicate that the odds of Level B and Level KA severity outcomes compared to PDO is 105% and 172% higher for drivers with suspended driver license; these results are expected due to the risky behavior of these drivers. Speeding often contributes to more severe crashes. The modeling results show that vehicle speeding increases the odds of Level KA severity outcome by 2.8 times. The modeling results indicate that the odds of Level C severity outcome increases by 58% compared to PDO when the driver is distracted.

Table 35: Modeling Results for Interstates Crash Severity

Variables		Estimate (Std.)			Odds Ratio		
		C	B	KA	C	B	KA
Intercept		-1.476 (0.288)	-1.099 (0.284)	-2.272 (0.451)	-	-	-
Driver Age	Middle	-	0.326 (0.145)	0.604 (0.291)	-	1.386	1.829
	Older	-	0.544 (0.253)	1.452 (0.389)	-	1.723	4.271
Male Driver Indicator	Male	-0.481 (0.130)	-0.345 (0.142)	-	0.618	0.708	-
Driver License	Suspended	-	0.721 (0.376)[1]	1.001 (0.527)[1]	-	2.056	2.722
Driver Speed	Speeding	-	-	1.336 (0.721)[1]	-	-	3.803
Distractions	Distracted	0.455 (0.258)[1]	-	-	1.577	-	-
Seatbelt	Not Wearing	1.834 (0.336)	2.379 (0.314)	3.308 (0.383)	6.257	10.789	27.331
Crash Type	Rollover	-	1.472 (0.348)	1.167 (0.684)[1]	-	4.356	3.212
Time of Day	Peak	0.285 (0.128)	-	-	1.330	-	-
Nighttime and OUI	Yes	-	-	1.277 (0.453)	-	-	3.585
Speed limit	≥ 70 mph	0.471 (0.150)	-	-	1.601	-	-
Grade	Not Level	0.516 (0.141)	-	-	1.676	-	-
Season	Winter	-	-0.686 (0.247)	-1.711 (0.373)	-	0.504	0.181
Surface Condition	Not Dry	-	-0.313 (0.156)	-1.199 (0.295)	-	0.731	0.302
Temperature	> 60°F	-	-	-0.910 (0.365)	-	-	0.402
AIC		3,804					
Log-Likelihood		-1,854.08					
McFadden's R^2		0.077					

[1] Variable statistically significant at 90% otherwise significant at 95%.

[2] The empty cells show that the variable is not statistically significant to the respective model or not applicable.

The modeling results shows a significant association between the severity of crashes and use of seatbelt. Given a crash, the odds of Level C severity outcome increases by over 5.2 times, Level B outcome by over 9.8 times, and Level KA outcome by over 26.3 times when seat belt is not used, compared to the crash resulting in PDO. The odds of Level B and Level KA severity outcomes increases by 3.4 and 2.2 times compared to PDO when the vehicle rolls over. The modeling results show that crashes that occur during the peak hours have higher odds of resulting in Level C severity outcomes (about 33% more). Combination of nighttime and operating under the influence was a significant variable for Level KA severity outcome. The odds of a crash resulting in a Level KA severity outcome is more than 2.5 times higher when a driver is operating under the influence at the nighttime (between dawn and dusk). For interstate facilities, the odds of a crash resulting in Level C injury outcome increases by 60% when the speed limit is greater than 70 mph. These results are expected since higher vehicle speeds often result in more severe crashes. The odds of resulting in Level C injury outcome increases by 68% compared to PDO when the roadway is not level, likely due to reduced visibility.

Given a crash, the odds of Level B and Level KA severity outcomes, respectively, decreases by 50% and 82% compared to the PDO during the winter period (November–April). These results are expected as in winter, interstates experience over 2.5 times more PDO crashes. Despite the significant increase in PDO crashes, the number of severe crashes remain more or less the same. In other words, although the inclement weather causes more PDO crashes, it does not increase the severity of crashes, due to presumably more cautious driving behavior under bad weather conditions. Given a crash, the odds of Level B and Level KA severity outcomes decreases by 27% and 70%, respectively, compared to PDO when the surface is not dry. Again, this observation is likely due to the cautious driving behavior. The odds of Level KA severity outcome (compared to PDO outcome) also decreases by 60% for days with temperature of 60°F or above.

Minor arterial facilities crash severity

Table 36 shows the modeling results for rural minor arterial roadways. The modeling results show that, given a crash, the odds of Level B and Level KA severity outcomes compared to PDO is respectively 1.4 and 1.5 times higher, respectively, for older drivers compared to young drivers. Given a crash, the odds of Level C and Level B crash outcomes is about 30% smaller for male drivers compared to female drivers. As discussed, drivers with suspended licenses are expected to be involved in more severe crashes due to their risky behavior. This observation was reflected in modeling results for minor arterials as well. The odds of Level C, Level B, and Level KA severity outcomes respectively increases by 64%, 170%, and 287% compared to PDO for drivers with suspended license. The modeling results also show that the odds of Level C severity outcome increases by 42% when the driver is under the influence. Not wearing a seatbelt has the largest impact on severity of crashes for minor arterials as well. Failing to wear a seatbelt increases the odds of Level C, Level B, or Level KA severity outcomes by 1.9, 3.8, and 23.1 times compared to PDO, respectively. Crash severity increases when a rollover crash occurs. Given a crash, vehicle rollover increases the odds of Level C, Level B, and Level KA severity outcomes by 1.4, 1.7, and 2.7 times, respectively, compared to PDO. For road segments with a posted speed limit of greater than 45 mph the odds of a crash resulting in Level C severity outcome increases by 46%. When a crash occurs on a curved segment, the odds of Level B severity outcome compared to PDO increases by 29%.

Table 36: Modeling Results for Minor Arterials Crash Severity

Variables		Estimate (Std.)			Odds Ratio		
		C	B	KA	C	B	KA
Intercept		-0.923 (0.220)	-1.310 (0.273)	-3.232 (0.483)	-	-	-
Driver Age	Older	-	0.875 (0.235)	0.918 (0.440)	-	2.398	2.504
Male Driver Indicator	Male	-0.344 (0.120)	-0.360 (0.163)	-	0.709	0.698	-
Driver License	Suspended	0.493 (0.290)[1]	0.994 (0.332)	1.354 (0.478)	1.637	2.702	3.871
Sobriety	OUI	0.351 (0.192)	-	-	1.420	-	-
Seatbelt	Not Wearing	1.066 (0.221)	1.561 (0.250)	3.183 (0.296)	2.905	4.764	24.107
Crash Type	Rollover	0.870 (0.307)	0.988 (0.394)	1.316 (0.568)	2.388	2.685	3.728
Speed Limit	≥ 45 mph	0.376 (0.175)	-	-	1.456	-	-
Curve	Present	-	0.255 (0.158)[1]	-	-	1.291	-
Season	Winter	-0.591 (0.138)	-0.784 (0.182)	-1.039 (0.298)	0.554	0.456	0.354
Surface Condition	Not Dry	-	-0.373 (0.190)	-0.996 (0.357)	-	0.689	0.369
Snow	≥ 1 inch of snow	-0.310 (0.187)[1]	-0.679 (0.316)	-	0.733	0.507	-
AIC		3,565					
Log-Likelihood		-1,743.62					
McFadden's R^2		0.092					

[1] Variable statistically significant at 90% otherwise significant at 95%.

[2] The empty cells show that the variable is not statistically significant to the respective model or not applicable.

For minor arterials, the PDO crashes increases during the winter period by about 2.7 times; however, severe crashes (KA, B, and C outcomes) do not increase in proportion to PDOs. This observation was reflected in modeling results as well. During the winter period, the odds of Level C, Level B, and Level KA severity outcomes decreases by 45%, 54%, and 65%, respectively, in comparison to the PDO severity outcome. On roadways with surface conditions that are described as not dry, the odds of Level B and Level KA severity outcome decreases by 31% and 63%, respectively, compared to the PDO severity outcome. For minor arterials, the odds of Level C and Level B severity outcomes decreases by 27% and 50% (compared to PDO crashes) during the days with at least 1 inch of snowfall.

Major collector facilities crash severity

Table 37 shows the modeling results for rural major collector roadways. For middle-aged drivers, the modeling results show increased odds of 45% in Level KA severity outcomes compared to younger drivers. Likewise, for older drivers, the odds of Level C, Level B, and Level KA outcomes increases by 90%, 39%, and 243%, respectively, compared to young drivers. The results show that, given a crash, the odds of Level C and Level KA severity outcomes is, respectively, 38% and 30% lower for male drivers compared to female drivers. When drivers are under the influence of drugs or alcohol, it is expected that they are involved in more severe crashes due to more reckless or aggressive driving behavior. When operating under the influence, the odds of Level C, Level B, and Level KA severity outcomes increases by 45%, 74%, and 134%, respectively, compared to PDO. In addition, the odds of crashes result in Level C and Level KA severity outcomes compared to PDO increases by 100% and 419%, respectively, when it is both nighttime and the driver is speeding.

As with interstates and minor arterials, there is a significant association between injury/fatality outcomes (KA, B, and C outcomes) and not wearing a seatbelt. When occupants are not using seatbelts, the odds of Level C, Level B, and Level KA severity outcomes compared to PDO increases by 1.8, 3.6, and 21.7 times, respectively. Vehicle rollover increases the odds of Level C, Level B, and Level KA severity outcomes by 1.4, 1.8, and 2.8 times, respectively (compared to the PDO outcome). The odds of Level B severity outcome decreases by 18% compared to PDO during the peak hour, likely because of congestion and speed reduction during peak hours. The odds of a crash leading to Level C, Level B, and Level KA severity outcomes increases by 23%, 23%, and 126%, respectively, on roads with speed limit of 45 mph or above. When crashes occur on curved segments, the odds of Level B or Level KA severity outcomes compared to PDO increases by 23% and 37%, respectively.

Table 37: Modeling Results for Major Collectors Crash Severity

Variables		**Estimate (Std.)**			**Odds Ratio**		
		C	**B**	**KA**	**C**	**B**	**KA**
Intercept		-0.694 (0.177)	-1.678 (0.228)	-4.202 (0.400)	-	-	-
Driver Age	Middle	-	-	0.370 (0.171)	-	-	1.448
	Older	0.645 (0.126)	0.328 (0.175)^{1}	1.231 (0.250)	1.905	1.387	3.426
Male Driver Indicator	Male	-0.472 (0.076)	-	-0.345 (0.170)	0.624	-	0.708
Sobriety	OUI	0.374 (0.131)	0.556 (0.147)	0.852 (0.203)	1.454	1.744	2.344
Nighttime and speeding	Yes	0.690 (0.322)	-	1.647 (0.404)	1.993	-	5.189
Seatbelt	Not Wearing	1.023 (0.138)	1.518 (0.147)	3.123 (0.178)	2.782	4.563	22.715
Crash Type	Rollover	0.875 (0.185)	1.044 (0.223)	1.330 (0.332)	2.398	2.840	3.779
Time of Day	Peak	-	-0.196 (0.102)^{1}	-	-	0.822	-
Speed Limit	≥ 45	0.204 (0.094)	0.207 (0.122)^{1}	0.816 (0.222)	1.226	1.230	2.261
Curve	Present	-	0.205 (0.098)	0.313 (0.159)	-	1.228	1.368
Season	Winter	-0.565 (0.134)	-0.401 (0.168)	-0.594 (0.282)	0.568	0.670	0.552
Surface Condition	Not Dry	-	-0.490 (0.123)	-	-	0.613	-
Snow	≥ 1 inch of snow	-0.230 (0.116)	-0.865 (0.183)	-1.520 (0.483)	0.795	0.421	0.219
Temperature	> 60°F	-	-	0.584 (0.274)	-	-	1.793

Variables		Estimate (Std.)			Odds Ratio		
		C	B	KA	C	B	KA
Precipitation	Yes	-	0.187 (0.107)[1]	-	-	1.205	-
	AIC	8,956					
	Log-Likelihood	-4,430.03					
	McFadden's R^2	0.096					

[1] Variable statistically significant at 90% otherwise significant at 95%.

[2] The empty cells show that the variable is not statistically significant to the respective model or not applicable.

During the winter period, major collectors experience 2.9 times more PDO crashes than they do during the non-winter period. However, the severe crash outcomes do not increase in proportion to the PDOs. The odds of Level C, Level B. and Level KA severity outcomes decreases by 43%, 33%, and 45%, respectively, during the winter period in comparison with the PDO outcome. The odds of Level B severity outcome decreases by 39% when the surface is not dry in comparison with the PDO severity outcome. The severity of crashes decreases on days with at least 1 inch of snow accumulation as well. During inclement weather, especially winter conditions, drivers slow down due to slippery conditions and lower visibility; therefore, the negative correlation with severe crashes is expected. During snow days with more than 1 inch of snow, the odds of Level C, Level B, and Level KA severity outcomes decreases by 20%, 58%, and 78%, respectively. On days that the maximum temperature is above 60°F, the odds of crashes resulting in Level KA severity outcome increases by about 79%. These results are different from the interstates results, perhaps due to narrow lanes and smaller shoulders, more congestion on major collectors, as well as increase in speeding behaviors during warmer weather. Precipitation increases the odds of level B-level crash severities by 20% compared to days without precipitation.

Minor collector facilities crash severity

Table 38 shows the modeling results for rural minor collector roadways. The results show increased odds of 58% in Level KA severity outcomes for middle-aged drivers compared to young drivers. The odds of level B and level KA crash severity compared to PDO is, respectively, 68% and 266% higher for older drivers compared to younger drivers. The results show that, given a crash, the odds of Level C and Level B severity outcomes increases by 48% and 22%, respectively, for male drivers compared to female drivers. The speeding variable was significant for Level C, Level B, and Level KA severity outcomes for minor arterials. These results are expected as speeding may result in losing the control of the vehicle; higher speeds also result in more severe impact. The modeling results show that the odds of Level C, Level B, and Level KA severity outcomes increases by 58%, 123%, and 148%, respectively, when drivers are speeding.

Table 38: Modeling Results for Minor Collectors Crash Severity

Variables		Estimate (Std.)			Odds Ratio		
		C	B	KA	C	B	KA
Intercept		-1.026 (0.190)	-1.720 (0.247)	-3.917 (0.458)	-	-	-
Driver Age	Middle	-	-	0.458 (0.256)[1]	-	-	1.581
	Older	-	0.517 (0.268)[1]	1.298 (0.397)	-	1.677	3.661
Male Driver Indicator	Male	-0.655 (0.114)	-0.251 (0.151)[1]	-	0.520	0.778	-
Drive Speed	Speeding	0.455 (0.277)[1]	0.802 (0.300)	0.907 (0.409)	1.576	2.231	2.476
Seatbelt	Not Wearing	1.423 (0.206)	1.618 (0.230)	2.659 (0.276)	4.149	5.043	14.276
Crash Type	Rollover	0.576 (0.270)	-	-	1.779	-	-
Nighttime and OUI	Yes	-	0.971 (0.259)	0.962 (0.360)	-	2.641	2.616
Speed Limit	≥ 45mph	-	0.380 (0.170)	0.930 (0.301)	-	1.462	2.534
Curve	Present	-	-	0.634 (0.262)	-	-	1.884
Grade	Not Level	0.243 (0.114)	-	-	1.275	-	-
Season	Winter	-	-0.573 (0.182)	-0.663 (0.272)	-	0.564	0.516
Surface Condition	Not Dry	-0.490 (0.142)	-0.393 (0.188)	-0.623 (0.292)	0.675	0.613	0.536
Snow	≥ 1 inch of snow	-0.400 (0.161)	-	-1.245 (0.621)	0.671		0.288
AIC		4,012					
Log-Likelihood		-1,964.144					
McFadden's R^2		0.085					

[1] Variable statistically significant at 90% otherwise significant at 95%.

[2] The empty cells show that the variable is not statistically significant to the respective model or not applicable.

As with previous facilities, not wearing a seat belt is the most influential factor in severity of crashes on minor collectors. The odds of a crash leading to Level C, Level B, and Level KA severity outcomes increases by 3.1, 4, and 13.3 times, respectively, compared to PDO when a seatbelt is not used. The odds of Level C severity outcome increases by 78% compared to PDO when the vehicle rolls over. The modeling results show that, given a crash, the odds of Level B and Level KA severity outcomes increase by 162% compared to PDO when it is nighttime and the driver operates under the influence. The results show that the odds of Level B and Level KA severity outcomes increases by 46% and 153%, respectively, when the speed limit is 45 mph or greater. The odds of a crash leading to a Level KA severity outcome increases by 88% on curved segments. Likewise, the odds a crash leading to a Level C severity outcome increases by 28% when the roadway segment is not level.

During the winter period, minor collectors experience 3.1 times more PDO crashes than during the non-winter season. However, the number of severe crashes remains more or less the same. For minor collectors, the modeling results indicate that during the winter period, the odds of Level B and Level KA severity outcomes decreases by 44% and 48%, respectively, in comparison to the PDO outcome. Likewise, the odds of Level C, Level B, and Level KA severity outcomes is decreased by 34%, 38%, and 46%, respectively, when the surface is not dry. On days with at least 1 inch of snow, the odds of level C and level KA severity outcomes decreases by 33% and 71%, respectively, in comparison to the PDO outcome.

Summary: Crash Severity

In Maine, lane departure crashes are the leading cause of crash fatalities. A majority of these crashes occur on rural roadways. Maine is a unique state, with aging infrastructure and population, a challenging climate, and diverse terrain. This study used Multinomial Logit Regression model to estimate severity outcome models for four facility types (interstates, minor arterials, major collectors, and minor collectors) to analyze the impact of roadway, driver, and weather factors on severity of crashes. The older drivers (aged 65 and older) variable was significant for all analyzed facilities. Crashes that involved older drivers showed increased odds of Level KA severity outcome by 327%, 150%, 243%, and 266% on interstate, minor arterials major collectors, and minor collectors, respectively, compared to younger drivers. Failure to use a seatbelt was the most influential variable leading to severe crashes. When the seatbelt is not used, the odds of Level KA severity outcome increases by 26.3, 23.1, 21.7, and 13.3 times higher compared to PDO on interstate, minor arterials, major collectors, and minor collectors, respectively. During the winter period, there are significantly more PDO crashes for each facility type; however, the severity of crashes does not necessarily increase in proportion to PDOs. The results show that the odds of crashes resulting in Level KA severity outcome in the winter decreases by 82%, 65%, 45%, and 48% for interstate, minor arterial, major collectors, and minor collector facilities, respectively, in comparison to the PDO outcome. We also mapped the crash data to daily weather data obtained from weather stations to use various weather variables in the model. The modeling results show that crashes that occur on snow days have decreased odds of resulting in Level KA severity outcome by 78% and 71% on major and minor collectors, respectively. When the surface is not dry, the odds of Level KA severity outcome decreases by 70%, 63%, and 46% on interstates, minor arterials, and minor collectors, respectively, in comparison to the PDO outcome. Inclement weather or bad surface conditions result in more PDO but less severe crash outcomes since drivers are more cautious, use lower speeds, and are more aware in these conditions.

Glossary of Terms

A. **Anti-icing:** Anti-icing is a philosophy, not a specific practice. It refers to treatment focused on preventing development of a bond between ice and the roadway, as opposed to removing ice and snow after a storm. Anti-icing requires attention to weather information and road conditions. Anti-icing may include pre-wetting salt or pre-treating the roadway.

B. **De-icing:** The winter road maintenance practice familiar to most people – plowing the roads and applying a mixture of salt and sand to break the bond of ice with the pavement, improve traction and promote melting. Plowing is commonly started after an inch of snow has accumulated on the roads, and a salt and sand mixture is spread. Sanding provides temporary traction while salt melts snow and ice so it can be cleared by plows.

C. **Centerline Miles:** The actual length of roadway in one direction of travel. Opposing travel lanes on some state highways are separated by large medians, this can result in the total length of highway differing for each direction.

D. **Lane Miles:** A measurement of roadway distance based on a single lane of travel. For example, one mile of a two lane road would constitute two lane miles.

E. **Pre-treating:** Pre-treating refers to direct application of liquid brine to the road before a storm.

F. **Pre-wetting:** Pre-wetting refers to the wetting of solid salts as they are spread onto the road by the service trucks. Pre-wetting may be performed at the storage area or at the spreader.

G. **State Aid Road:** These roads connect local roads to the state highway system and generally serve intracounty rather than intrastate traffic movement. With the exception of compact areas, the state aid roads are usually maintained by MaineDOT in the summer and by municipalities in the winter pursuant to State Law 23 MRSA 1003. The state aid highway category generally corresponds with the federal “collector” classification.

H. **State Highway:** A system of connected main highways throughout the state that primarily serve intra- and interstate traffic. With the exception of compact areas, the MaineDOT has responsibility for the year-round maintenance of state highways. The state highway category generally corresponds with the federal “arterial” classification.

I. **Toll Road:** In Maine, these are all roads maintained by MTA.

J. **Townway:** These roads are all roads not included in the state highway or state aid highway classifications that are maintained by municipalities or counties. These roads are classified as federal “local” roads.

K. **Winter Road Chemicals**:

    a. **Sodium chloride ($NaCl$)**, or road salt, is the most widely used chemical for winter road maintenance. It is used in solid form as rock salt, or liquid form as brine. As brine, it is used for pre-treating.

    b. **Calcium chloride ($CaCl_2$)** is used to lower the working temperature of rock salt. **Magnesium chloride ($MgCl_2$)** is used to lower the working temperature of rock salt. It is used in some states to pre-treat roads.

c. **Calcium magnesium acetate (CMA)** is used to lower the working temperature of rock salt. Sometimes used in environmentally sensitive areas, it is extremely expensive.
d. **Potassium acetate (KA)** can be used to lower the working temperature of rock salt. It is more expensive and less commonly used than chlorides.

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Appendix 1: Survey Instrument for Municipal Winter Operations

The University of Maine and the MaineDOT are conducting a statewide survey of municipalities to better understand winter road maintenance practices. The project will also update the 2010 report entitled Maine's Winter Roads: Salt, Safety, Environment and Cost.

A majority of Maine's road miles are maintained by municipalities. Your responses in the following categories will help us create a picture of the winter practices of cities and towns throughout Maine. Even if your town contracts out all winter work, we'd like to hear from you.

<u>**Please tell us about your town or city's winter operations:**</u>

Municipality name ______________________________ current population __________________

Winter road miles you maintain: ____________________ centerline miles

Do your winter operations include sidewalks or parking lots? Yes___ No ___

Sidewalks: __________miles Schools, municipal lots, other: _________square footage

What percentage of your winter miles are:

1) highest priority ____

2) medium priority ____

3) last priority ____

For winter operations, how much of your town's centerline miles is maintained by the following?

municipal crews/equipment ____

private contractor ____

comments? ____

If you use a contractor for winter maintenance, do their drivers receive any training on snow and ice control practices? ____

If you use municipal crews, do your drivers receive any training on snow and ice control practices?

____

COST

What was your town's total winter maintenance budget during 2019-2020? $ _______________

If known, how does that break down into:

approx. % personnel costs _______________________

approx. % materials ____________________________

approx. % equipment___________________________

MATERIALS

In the winter of 2019-2020:

How many tons of salt (sodium chloride) did you buy? ________ What % did not get used? ______

How many cu. yds. of sand did you buy? ___________________ What % did not get used? ______

Which other de-icers did you buy?

__ Calcium chloride (CaCl2): How much?_________ in gallons or tons?_____

What % did not get used? _____

__ Magnesium chloride (MgCl2): How much?_______ in gallons or tons?____

What % did not get used? _____

__ Other de-icer (which?) _______ How much?______ in gallons or tons?____

What % did not get used? _____

WINTER PRACTICES

Do you consider your municipal winter operations to be more of

__________ an "anti-icing approach with salt" or

__________ the more traditional method of "sand- with-some-salt-in-it"?

Do you pre-treat your roads (applying liquids before a winter storm)?

____Yes ____ No If yes, how often do you pre-treat? _________________________

Do you pre-wet your materials? _____ Always _____ Sometimes _____ Never

Does your municipality have a defined Level of Service policy for winter maintenance?

Yes____ No____ How is it communicated to your residents?______________________

Are there areas in the road mileage you maintain which are considered environmentally sensitive (wetlands, wildlife management areas, public water supply) or which otherwise require specific/different winter maintenance? Please explain.

____

Are you familiar with the [Maine Environmental Best Management Practices (BMP) Manual for Snow and Ice Control](#)? Yes___ No ____

Do you use this manual in your work or training? ______________________________

Has your town ever had a well claim for salt contamination? ____________________________

Are there any other winter practices you use that we have not asked about here?
Please comment on anything that makes your town's winter maintenance practices or costs unique.
____

____

In case we need to follow up on any of these questions, could you please provide a contact for your town?

Name: ____

Email address: _____________________ Phone number: ___________________________

Thank you for taking this survey! Your response is very important to us.

Please return the survey by email or postal mail to:
Peggy McKee
Email: margaret.mckee@maine.edu
Mailing: Margaret Chase Smith Policy Center, 5784 York Complex, #4, Orono, ME 04469-5784

Appendix 2: Further Resources

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