WINTER HIGHWAY MAINTENANCE OPERATIONS: CONNECTICUT

JULY 2015

<u>A REPORT BY</u>

THE CONNECTICUT ACADEMY OF SCIENCE AND ENGINEERING

<u>FOR</u>

THE
CONNECTICUT DEPARTMENT OF TRANSPORTATION

Winter Highway Maintenance Operations: Connecticut

A Report By

The Connecticut Academy of Science and Engineering

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This study was initiated at the request of the Connecticut Department of Transportation on June 1, 2014. The project was conducted by an Academy Study Committee with the support of the UConn Transportation Institute, with James Mahoney serving as Study Manager. The content of this report lies within the province of the Academy's Transportation Systems Technical Board. The report has been reviewed on behalf of the Academy's Council by Academy Members John N. Ivan, PhD, Herbert S. Levinson, DrEng, PE, and external reviewer Ron Wright, Idaho Transportation Department. Martha Sherman, the Academy's Managing Editor edited the report. The report is hereby released with the approval of the Academy Council.

Richard H. Strauss
Executive Director

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16. Abstract: This study addresses issues identified in legislation adopted by the Connecticut General Assembly that directed the Commissioner of Transportation to conduct an analysis of corrosive effects of chemical road treatments, determine the cost of corrosion created by road treatments, and to provide an evaluation of alternative techniques and products, such as, but not limited to, rust inhibitors, with a comparison of cost and effectiveness. Primary conclusions of the study include that ensuring the safety and mobility of the traveling public requires the most effective winter highway maintenance practices possible. This is a shared responsibility—to achieve comprehensive and sustainable success, competing factors must be considered including safety, cost, corrosion, operating practices, materials and equipment, environmental and economic impacts, and communication with the general public, stakeholders, and government leaders. Balancing these factors presents a challenge that can be met through ongoing monitoring and continuous improvement based on evolving best practices. While use of chloride-based deicing chemicals for winter highway maintenance has raised concerns regarding impacts on vehicles, infrastructure and the environment, alternative products also have environmental, corrosion and expense impacts. Although corrosion inhibitors are available for use with deicers, evidence of their effectiveness in the field based on literature reviewed was not found. Research is needed to confirm their effectiveness before considering use. Further, CTDOT's participation in national initiatives, and ongoing communication with neighboring states, municipalities, and other stakeholders should continue and be strengthened to help balance the competing factors by using the most effective practices.

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MEMBERS OF THE STUDY COMMITTEE ON WINTER HIGHWAY MAINTENANCE OPERATIONS: CONNECTICUT

Paul Brown
Snow and Ice Engineer
District 1, MassDOT

Brian Burne
Highway Maintenance Engineer
Maine Department of Transportation

Sten Caspersson, *(Academy Member)*
Consultant, Nuclear Power

Michael J. Gantick, PE, PWLF
Director of Public Works
Town of South Windsor

Monty Mills
Maintenance & Operations Branch Manager
Washington State DOT (ret.)

Richard Nelson, PE, F.ASCE
Coordinator, Snow and Ice Pooled Fund
Cooperative Program, AASHTO

Laura E. Pence, PhD
Professor, Department of Chemistry
University of Hartford

Leland Smithson
Snow and Ice Pooled Fund Cooperative
Program, AASHTO, Iowa DOT (ret.)

Ex-Officio Member
Robert W. Turner, PE
Safety/Area Engineer
Connecticut Division, Federal Highway
Administration

STUDY REVIEWERS

John N. Ivan, PhD *(Academy Member)*
Professor & Associate Department Head, Civil & Environmental Engineering, UConn

Herb Levinson, DrEng, PE *(Academy Member)*
Professor of Civil Engineering (ret.), UConn

Ron Wright *(External Reviewer)*
Central Laboratory Manager, Division of Engineering Products & Plans,
Idaho Transportation Department

RESEARCH TEAM

CONNECTICUT TRANSPORTATION INSTITUTE (CTI), UCONN

Study Manager
James Mahoney, Executive Director, CTI

Research Engineers
Eric Jackson, PhD, Director, Connecticut Transportation Safety Research Center
Donald A. Larsen, PE, Temporary University Specialist, CTI
Timothy Vadas, PhD, Assistant Professor, Civil and Environmental Engineering
Kay Wille, PhD, Assistant Professor, Civil and Environmental Engineering
Scott Zinke, Research Engineer, Connecticut Advanced Pavement Laboratory, CTI

ACADEMY PROJECT STAFF

Richard H. Strauss, Executive Director
Terri Clark, Associate Director
Ann G. Bertini, Assistant Director for Programs

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LIST OF ACRONYMS AND ABBREVIATIONS

°F	Degrees Fahrenheit
2009/2010	Winter season crossing two calendar years
µS/cm	Electrical Conductivity (micro siemens per centimeter)
10:1	10 parts mixed with 1 part
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
ACR	Alkali Carbonate Reaction
AOT	Agency of Transportation (Vermont)
ASCE	American Society of Civil Engineers
ASR	Alkali Silica Reaction
ASTM	American Society of Testing and Materials
ATA TMC	American Trucking Association Truck Maintenance Council
AVL	Automatic Vehicle Location
BOD	Biochemical (or Biological) Oxygen Demand
$CaCl_2$	Calcium Chloride
CASE	Connecticut Academy of Science and Engineering
CASHO	Connecticut Association of Street and Highway Officials
CGA	Connecticut General Assembly
COD	Chemical Oxygen Demand
CRCOG	Capital Region Council of Governments
CMA	Calcium Magnesium Acetate
C-S-H	Calcium Silicate Hydrate
CTCDR	Connecticut Crash Data Repository
CTDOT	Connecticut Department of Transportation
CTI	Connecticut Transportation Institute, UConn
CY	Calendar Year
DAS	Connecticut Department of Administrative Services
DEEP	Connecticut Department of Energy and Environmental Protection
DOD	US Department of Defense
DOT	US Department of Transportation (also referred to as USDOT)
DPH	Connecticut Department of Public Health
EMS	Emergency Medical Services
EPA	US Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
F/T	Freeze-thaw Cycling
GIS	Geographic Information System
GPS	Geographic Positioning System
HMWM	High Molecular Weight Methacrylate
IPRF	Innovative Pavements Research Foundation
KABCO	Injury classifications system for crash victims (see Glossary of Terms)
KAc	Potassium Acetate
Lbs.	Pounds

LD_{50}	A lethal dose at which 50% mortality occurs
L	Liters
(LMC/OBPE)	Liquid Magnesium Chloride/Organic-based Performance Enhancers
MaineDOT	Maine Department of Transportation
MAIS	Maximum Abbreviated Injury Scale (see Glossary of Terms)
MassDOT	Massachusetts Department of Transportation
MCL	Maximum Contaminant Level
$MgCl_2$	Magnesium Chloride
MSDS	Material Safety Data Sheet
M-S-H	Magnesium Silicate Hydrate
NaCl	Sodium Chloride
NACE	National Association of Corrosion Engineers
NCHRP	National Cooperative Highway Research Program
NHDOT	New Hampshire Department of Transportation
NHTSA	National Highway Traffic Safety Administration
NJDOT	New Jersey Department of Transportation
NYSDOT	New York State Department of Transportation
OE	Original Equipment
PCA	Portland Cement Association
PCC	Portland Cement Concrete
PNS	Pacific Northwest Snowfighters Association
ppm	Parts per Million
QALYs	Quality-Adjusted Life-Years
Ref.	Reference
RCI	Road Condition Index
RIDOT	Rhode Island Department of Transportation
RWIS	Road Weather Information System
SAE	Society of Automotive Engineers
sq-mi	Square miles
STD	Standard (Volvo)
TMDLs	Total Maximum Daily Loads
TRB	Transportation Research Board
USDOT	US Department of Transportation (also referred to as DOT)
USGS	United States Geological Survey
UV	Ultra-violet light
VAOT	Vermont Agency of Transportation (also referred to as AOT and VTrans)
VMT	Vehicle Miles Travelled
W/D	Wet-dry Cycling
WSI	Winter Severity Index
WTI	Western Transportation Institute, Montana State University

EXECUTIVE SUMMARY

At the request of the Connecticut Department of Transportation (CTDOT), the Connecticut Academy of Science and Engineering conducted this study on Winter Highway Maintenance Operations. The study addresses the issues identified in Section 6 of Public Act 14-199 that directed the Commissioner of Transportation to *conduct an analysis of the corrosive effects of chemical road treatments on 1) state snow and ice equipment vehicles, 2) state bridges, highways and other infrastructure, and 3) the environment; The analysis shall determine the cost of corrosion created by road treatments, and shall include an evaluation of alternative techniques and products, such as, but not limited to, rust inhibitors, with a comparison of cost and effectiveness.*

BRIEF STATEMENT OF PRIMARY CONCLUSION

Ensuring the safety and mobility of the traveling public requires the most effective winter highway maintenance practices possible. This is a shared responsibility—to achieve comprehensive and sustainable success, competing factors must be considered, including safety; cost; corrosion; operating practices; materials and equipment; environmental and economic impacts; and communication with the general public, stakeholders, and government leaders. Balancing these factors presents a challenge that can be met through ongoing monitoring and continuous improvement based on evolving best practices.

CTDOT winter highway maintenance operations are consistent with the practices of other states with similar weather conditions. Additionally, the department engages in an ongoing process of monitoring current practices, identifying areas for improvement, and instituting improvements based on best practices to increase mobility, safety and overall roadway conditions while reducing the amount of deicing chemicals used. CTDOT has been proactive by testing new technologies and implementing those shown to be effective. Additionally, municipalities can benefit from CTDOT's experience with implementation of state-of-the-art technologies shown to be effective—providing opportunities for achieving higher levels of service to the traveling public.

It is noted that while use of chloride-based deicing chemicals for winter highway maintenance has raised concerns regarding impacts on vehicles, infrastructure and the environment, alternative products also have environmental, corrosion and expense impacts. Although corrosion inhibitors are available for use with deicers, evidence of their effectiveness in the field based on literature reviewed was not found. Research is needed to confirm their effectiveness before considering use.

Further, CTDOT's participation in national initiatives, and ongoing communication with neighboring states, Connecticut municipalities, and other stakeholders, should be continued and strengthened to help balance the competing factors by using the most effective practices.

OVERVIEW

The study report includes the following chapters:

- Chapter 1: Background and Introduction – presents the purpose for the study and an outline of the report.
- Chapter 2: Overview of Snow and Ice Control Operations on Connecticut Roadways: CTDOT and Municipalities — includes a summary of a CTDOT report (Appendix C) providing information on the mission and operations of the department's winter highway maintenance program, practices, types and quantity of materials used, operational coordination, training and outreach, advances in technology, and operational improvements. Additionally, an analysis of responses from a survey of municipalities (Appendix D) on their winter highway maintenance practices is provided.
- Chapter 3: Deicing Chemicals Currently in Use in North America — provides a summary of deicing chemicals primarily used in North America, including their advantages and disadvantages, and approximate costs.
- Chapter 4: Winter Highway Maintenance Practices in Surrounding States — provides a five-year summary of winter highway practices that are used in neighboring New England states, New York and New Jersey, including a comparison of these practices to those used in Connecticut.
- Chapter 5: Environmental Impacts and Mitigation of Deicing Chemical Applications for Winter Highway Maintenance — discusses environmental impacts of deicing chemicals on soils, surface waters, groundwater and biology, as well as techniques to mitigate the impact of these materials.
- Chapter 6: Effects of Deicer Corrosion on Infrastructure and Vehicles — provides a technical overview and assessment of corrosion due to use of chemical deicers. The costs of corrosion, prevention options, and the condition of Connecticut's infrastructure and winter highway maintenance equipment are included. State of the art techniques for reducing and preventing vehicle and infrastructure corrosion are also addressed. Further, corrosion inhibitors and their advantages and disadvantages are also discussed.
- Chapter 7: Best Practices and New Technologies — presents new technologies and best practices as found in the literature and/or practiced in Connecticut and other winter-weather states.
- Chapter 8: Winter Highway Safety Analysis and Overview of Economic and Societal Impacts —includes information regarding highway safety, statistics and analysis of crash rates in Connecticut during winter weather conditions, economic impacts of winter weather events, and societal impacts of mobility during and after events.
- Chapter 9: Summary of Findings -- provides a summary of findings for winter weather practices.
- Chapter 10: Conclusions and Recommendations -- provides conclusions and recommendations for consideration to help guide effective and efficient winter highway operations.

RECOMMENDATIONS

CTDOT should continue to participate in groups such as Clear Roads, the American Association of State Highway and Transportation Officials (AASHTO), National Cooperative Highway Research Program (NCHRP) and Transportation Research Board (TRB) to remain current on best practices for snow and ice control. Participation in these groups will enable CTDOT to be aware of emerging best management practices and to adopt those that provide improved strategies that lead toward optimizing the department's winter highway maintenance operations (i.e., maximize impact of chemicals and minimize excess use of chlorides). CTDOT should also work to ensure that successful technology and operation improvements are shared with municipalities for their consideration and implementation. CTDOT should seek assistance from organizations such as the Connecticut Technology Transfer Center at UConn and the Connecticut Association of Street and Highway Officials, Inc. (CASHO), among others, for sharing winter highway operations practices and advancements with municipal transportation agencies.

The following recommendations are provided for consideration by CTDOT and Connecticut's municipalities. Some of the suggested recommendations have already been implemented by CTDOT and some municipalities.

Deicing Chemicals and Application Techniques

DEICING CHEMICALS

Currently, chloride-based snow and ice control chemicals are the most effective and economical treatments readily available, and will be the most commonly used deicing chemicals for the foreseeable future.

a. CTDOT should continue to use sodium chloride as the primary deicer; it remains the most economical inorganic chemical and is an effective deicer under most conditions above 20°F. While typically temperatures in Connecticut under most winter weather conditions are above 20°F, for lower temperatures, materials application rates may be varied due to conditions.

b. CTDOT should continue to mix brine (sodium chloride in solution with water) in-house, rather than purchase mixed materials containing unspecified additives.

c. While organic chemicals (i.e., potassium acetate, sodium formate and propylene glycol, among others) can potentially be used in very specialized circumstances or unique situations for snow and ice control, availability, cost and unintended environmental consequences from the breakdown of organics may be problematic.

PRE-WETTING

Pre-wetting is an effective practice that is used to moisten salt or sand (where still in use) prior to application. It reduces the tendency of these materials to bounce off the road and activates faster melting. CTDOT should continue, when feasible, to use sodium chloride solution for pre-wetting at the beginning and end of seasons and magnesium chloride solution during the coldest months, to assist in lowering the temperature at which the solid sodium chloride is effective.

a. The chloride-based chemical selected for the pre-wetting solution ideally should be determined based on forecasted temperatures during periods within the winter season. For example, sodium chloride solution can be used for pre-wetting during the warmer months at the beginning and end of the winter season, with magnesium chloride solution used generally mid-December through the end of February.

b. If uninhibited liquid calcium chloride solution is available and cost-effective, it should be considered for the pre-wetting solution in lieu of liquid magnesium chloride solution; while all chlorides are corrosive to metals, calcium ions are less damaging to Portland Cement Concrete (PCC) than magnesium ions.

PRE-TREATING

CTDOT should continue the use of sodium chloride solution for pre-treatment of bridges and known problem areas. Pretreating bridge decks, hills and shaded, north-facing roadways is an effective strategy for enhancing safety and reducing callout of maintenance personnel after hours, resulting in a reduction of overtime costs.

a. CTDOT's strategy of using sodium chloride solution as pre-treatment appears to be successful. Switching to a calcium chloride or magnesium chloride-based pre-treatment does not appear to be warranted in Connecticut's climate.

b. CTDOT should promote the use of sodium chloride solution pre-treatment in larger municipalities for problematic areas.

c. CTDOT should promote the use of solid proprietary salt or pre-wetted salt for pretreating in smaller municipalities.

ANTI-ICING STRATEGY

CTDOT should continue with the anti-icing strategy that was initiated during the winter of 2006/2007 to shorten the period of time that roads are snow or ice covered, to ease removal of snow and ice, and to assist in reducing winter weather-related vehicle crashes.

CORROSION INHIBITORS

Corrosion inhibitors may assist in delaying the onset of corrosion for spreading and plowing equipment. However, for proprietary salts that include a corrosion inhibitor, in many cases the additive is not disclosed, and therefore its effect on the surrounding environment is not known. Based on the reviewed literature, evidence of effectiveness of corrosion inhibitors outside of the laboratory is inconclusive, and it is noted that the dilution of concentration of a corrosion inhibitor occurs rapidly with the melting of snow and ice. As the effectiveness of corrosion inhibitors for the motoring public was not found, the practice of introducing additional chemicals to the environment is questionable, especially when their exact composition is unknown. Additional study regarding the effect of the use of corrosion inhibitors to reduce corrosion to infrastructure and vehicles is suggested. CTDOT should continue to monitor the findings of other agencies and future studies on effectiveness of corrosion inhibitors before implementing their use.

Infrastructure

PROTECT STRUCTURES

All chloride-based deicing chemicals cause corrosion. Therefore it is very important to promote the use of materials that reduce or prohibit chloride penetration into concrete and steel structures. This includes the following:

a. Use low-permeability concretes for new bridge decks

b. Use sealers and crack sealers on new bridge decks and appropriate components to slow chloride penetration

c. Ensure proper curing of concrete to minimize micro-cracking that results in pathways for the chlorides to penetrate into a structure

d. CTDOT should re-establish a bridge painting (coatings) program for steel structures

BRIDGE CLEANING

It seems obvious that the removal of salt deposits from bridge structures would be beneficial for minimizing the impacts of these chemicals. It is noted that the literature reviewed for this study did not provide consistent conclusive evidence that cleaning bridge decks and structures is cost-effective. This may be due both to the difficulty in quantifying the benefits of removing the salts and the long-term study periods required to validate the benefits. Therefore, the following focused approach for bridge cleaning is recommended.

a. Develop and fund a long-term bridge rinsing/cleaning program to remove chlorides as well as any debris that may hold moisture, particularly for steel portions of structures. Particular attention should be paid to parts of the structure most prone to corrosion such as joints, support ends, fasteners, drainage structures and steel components.

b. Remove a majority of the chlorides during the spring, when stream flows are typically higher than other times of the year, to minimize environmental impacts.

BRIDGE MAINTENANCE

CTDOT and municipalities should continue to utilize best management practices for bridge maintenance, including the following:

a. Maintain bridge joints to limit water infiltration into bridge structures.

b. Minimize runoff containing chlorides from penetrating the bridge structures.

c. Perform periodic bridge inspections in accordance with the National Bridge Inspection Standards 23 CFR 650 and schedule maintenance to address deficiencies such as cleaning, minor repairs, and maintenance of proper coatings on bridge steel in a timely manner.

d. Encourage use of bridge preservation and preventive maintenance strategies. CTDOT should provide technical guidance to municipalities to assist with implementing bridge preservation programs.

CORROSION-RESISTANT DESIGNS

During the design of bridges and for bridge rehabilitation projects, consider the use of anti-corrosion materials such as

a. epoxy-coated reinforcing steel in structure elements coming in contact with deicing materials such as bridge decks, concrete barriers, and drainage structures;

b. stainless or galvanized steel rebar in critical concrete structures; and

c. corrosion-resistant materials in curbs, median barriers, catch basins.

Vehicles

VEHICLE WASHING

An April 2015 National Highway Traffic Safety Administration (NHTSA) Safety Advisory recommended that vehicles older than the 2008 model year be washed as soon as possible after exposure to salt and chemicals. This safety advisory was considered in developing the following recommendations.

a. Vehicle washing be performed on all classes of vehicles, from commercial trucks to motorcycles, to dilute the effects of residual deicing chemicals. Washing should assist with the prevention of corrosion for all vehicles, regardless of age.

b. If salt neutralizers are used to wash vehicles, select products that have proven to be effective. Caution should be exercised in product selection, as research reviewed for this study found that some neutralizers used at the manufacturer's recommended concentration actually increased corrosion of some metals.

c. An emphasis should be placed on rinsing/washing the undercarriage of the vehicle.

COMMERCIAL CAR WASHES

Commercial car washes should be encouraged to voluntarily disclose/post information regarding whether recycled water or fresh (clean) water is used for the car wash, particularly for undercarriage washes. If recycled water is used, then the percent of recycled water used, what cycles the recycled water is used for, and any additives used should be disclosed. Additionally it is suggested that the Connecticut General Assembly and/or Connecticut Department of Consumer Protection and Connecticut Department of Energy and Environmental Protection (DEEP) consider regulations requiring the disclosure and posting of information on the use of recycled water for car washes.

a. Use of fresh water is encouraged for the final rinse – both on the surface and undercarriage washes.

b. Research is needed to identify acceptable salt concentrations of recycled water – that which would not be detrimental to vehicles.

Additionally, the development of additional commercial large truck/vehicle washing stations open to the public should be encouraged, as only one or two commercial large truck/vehicle washing stations are currently available in Connecticut.

CORROSION-RESISTANT TECHNOLOGY

The purchasers of commercial vehicles need to encourage vehicle manufacturers to continue to improve corrosion resistance of vehicles. This includes the use of composites, aluminum, paints and coatings, fasteners, and shrouding of critical electrical or mechanical vehicle components.

a. Use improved coatings for vulnerable components, including undercoating technologies.

b. Improve designs to eliminate known corrosion problems and areas where deicing chemicals can collect.

c. Eliminate areas where dissimilar metals come into contact with each other.

VEHICLE INSPECTIONS

There is a need for periodic voluntary undercarriage inspections of all vehicles (including passenger and commercial vehicles), particularly as vehicles age. This could possibly be performed during oil changes or other standard vehicle maintenance procedures. Other states have safety inspection programs that are required as part of the registration renewal process. Inspections could help prevent vital component failures such as brake lines or parts of the suspension system.

Environment

GENERAL CONSIDERATIONS FOR CHLORIDES

The use of deicing materials for winter highway maintenance has a variety of environmental impacts, some of which are more manageable than others. Some impacts are short term or seasonal, such as sudden spikes of chloride levels in soils, shallow groundwater or streams due to the flushing of deicing materials from those environments over time. Some impacts from chlorides are longer term, such as the increasing levels of chloride observed in groundwater over the past several decades. The impacts on roadside vegetation are very difficult to mitigate. Therefore any plantings (preferably native) along roadsides should have a tolerance for salt.

CHLORIDE-SENSITIVE ENVIRONMENTS

CTDOT as well as local municipalities need to periodically consult with the Connecticut Department of Public Health (DPH) and DEEP to identify sensitive environments or drinking water sources that are at risk of impairment due to chlorides. After identifying these locations, CTDOT and the local municipalities can work to reduce the application rates of chlorides in these areas. In these identified areas, it is suggested that signs be posted for safety purposes that identify areas where application rates of deicers will be reduced for environmental or public health reasons.

MULTI-CHEMICAL APPLICATION

Although other states such as Minnesota have developed the capability to switch chemicals on the fly, typically for applying alternative chemicals in environmentally sensitive areas, no current need for this was identified in Connecticut. This technology, however, should be monitored for possible future implementation in specifications for purchase of new winter maintenance vehicles.

SALT STORAGE

Covered salt sheds have been implemented statewide by CTDOT and virtually all municipalities. However, commercial salt storage may be an issue that deserves continued attention by DEEP or DPH.

SHARED RESPONSIBILITY

CTDOT in collaboration with DEEP should inform all parties involved with winter weather-related maintenance (i.e., state, municipal, commercial, private, and consumers) of and use best management practices to protect the environment.

REPORTING OF DEICERS APPLIED

Each transportation agency within Connecticut responsible for applying deicing chemicals should be required to report the quantity of materials applied during each winter season, and this information should be made available to the public. This will enable the public to better understand the types and quantities of materials being applied. By making this information public, it will allow municipalities to see how they compare to other municipalities that they would consider comparable in both size and climate. Disparities can be identified and used as a guide to improve practices and performance.

Outreach and Education

PUBLIC INFORMATION CAMPAIGN

CTDOT should develop a public service campaign that utilizes web-based and social media tools along with printed materials to educate the motoring public about winter highway maintenance operations and practices. This information would help explain

a. anti-icing procedures
b. chemicals in use (and why they are used)
c. level of service goals by road type (drivers typically have an expectation that roads will be clear several hours after a storm ends, but there are conditions for some winter weather events when this is not possible)

Additionally, CTDOT, with assistance from DEEP, should develop a handbook that provides guidance for best practices for winter maintenance of sidewalks and parking lots for the general public, businesses, and private winter maintenance service companies. Consideration should also be given to limiting liability for property owners when they have followed the established best practices pertaining to slip and fall accidents. Currently, the financial cost for applying copious amounts of deicing chemicals is far less than the costs associated with a single slip and fall injury claim.

MEDIA

The media is a source of information for the general public. However, the information shared with the public needs to be accurate. Informal information indicates that the general public believes that pre-treatment chemicals applied on roadways prior to winter weather events by CTDOT contain something other than what is actually used — a 23% solution of sodium chloride in water. Both natural processes and events cause corrosion to vehicles and infrastructure as well as chemicals used for winter highway maintenance by CTDOT, municipalities, and private winter maintenance activities.

Annual informational sessions conducted in advance of the winter season for the media about winter maintenance practices, and materials that will be used for pre-treatment and anti-icing, would help to dispel misconceptions. Informational sessions with the media, along with the availability of public information, will be useful in assuring factual information is distributed to the public. This will help to inform and clarify misconceptions regarding winter highway maintenance practices and materials that are used by CTDOT and municipalities.

RECORDKEEPING AND TRANSPARENCY

CTDOT and municipalities should each prepare an annual summary that accurately documents winter maintenance practices and the type of materials and quantities used for each winter season. The annual summaries should be publicly available and easily accessible.

a. CTDOT should make winter maintenance information readily available to the public via CTDOT's website. Other states, such as Maine, Minnesota, and Vermont, should be used for examples of best practices for transparency and information dissemination.

b. CTDOT should provide technical assistance and guidance to assure that the state's municipalities implement winter maintenance best practices for the 82% of the state's road network that is maintained by the municipalities.

c. Accurate recordkeeping is paramount to optimizing the use of deicers. Municipal data collected as part of this study indicates that it is possible that the towns are using greater amounts of magnesium chloride per ton of solid deicer than CTDOT. However, since there is no single repository or common format used for data collection, total material usage is not readily available. A repository for the collection of winter maintenance practices and material usage using a common reporting format should be developed.

d. Annual CTDOT and municipality winter maintenance information and data will provide an opportunity for comparisons and benchmarks between agencies for the purpose of continually improving operations throughout the state.

VOLUNTARY CERTIFICATION OF PRIVATE CONTRACTORS APPLYING DEICING CHEMICALS

The development of a voluntary certification program for private contractors who apply de-icing chemicals will be an opportunity to provide information and training to private contractors about best practices, including application rates. Certification programs of others such as the New Hampshire Department of Environmental Services' voluntary certification program for private contractors or the American Public Works Association program could be used as models for developing a Connecticut program. This certification could be used by private contractors to promote their business as being environmentally friendly regarding the application of deicing chemicals, and could be useful to businesses and the public in selecting contractors who are sensitive to the environmental issues. This certification could also be a requirement as part of limiting liability associated with slip and fall injury claims, as it is in New Hampshire.

The actual quantity of deicing chemicals applied by private contractors in Connecticut is unknown. However, information for New Hampshire indicates that the quantity of deicing chemicals used by private contractors in New Hampshire may approach half the total deicing chemicals applied in the state. With private contractors representing such a large percent of material being applied, private contractors represent a significant opportunity to reduce the quantity of salt material used in Connecticut.

COMMUNICATION

CTDOT should continue to communicate with neighboring states regarding winter highway maintenance best practices and operations. CTDOT should also continue its practice of communicating with neighboring states with regard to approaching winter weather events in order to provide as much lead time as possible for staging personnel and equipment.

Also, CTDOT should seek to communicate with municipalities with regard to information on weather, equipment, technology and best practices. In addition to CTDOT, organizations that can help to maximize outreach include the Connecticut Technology Transfer Center at UConn, CASHO, and others.

TRAINING

Initial and ongoing annual training on the best practices and methodologies should be provided for all CTDOT and municipal employees, and contractors involved in winter highway maintenance operations. This training should include

a. current state-of-practice
b. information about new technology
c. forums to discuss successes and problems encountered

This training can be provided by the Connecticut Technology Transfer Center at UConn, as well as in-house by CTDOT and others.

General

CTDOT should continue to monitor state-of-the-art techniques for winter maintenance and communicate with surrounding states about their winter maintenance practices. CTDOT should be cognizant of alternative chemicals that become available that might become acceptable substitutes for chlorides. Approaching any changes in the use of deicing chemicals regionally may help vehicle manufacturers design and modify their products to be more corrosion resistant, since each type of deicing chemical may have different effects on the various metals that are used in a vehicle.

LEVEL OF SERVICE

CTDOT should consider revising their definitions of levels of service for winter weather events on the three classes of state roadways that are maintained by CTDOT. Defining the level of service for the different roadway classes provides an opportunity for CTDOT to re-evaluate its policy of using a standard deicer application rate of 200 lbs./lane-mile. Utilizing variable application rates under differing conditions and roadway classifications may ultimately be more cost-effective and useful in helping to mitigate the negative impacts of using chloride-based deicers. Communicating with the public about road condition expectations following a winter weather event for the different classes of roadways, setting goals, and posting achievements may be useful for maintaining reasonable public expectations.

PERFORMANCE MEASURES

CTDOT should monitor in-process studies being undertaken by NCHRP Project 14-34 "Guide for Performance Measures in Snow and Ice Control Operations" [152] and Clear Roads Project 14-05 "Snow Removal Performance Metrics" for use in developing winter highway maintenance performance measures on mobility, chemical use, and cost similar to that done in some other states. A review of performance measures implemented by other states is also recommended.

WEATHER MONITORING

Road Weather Information Systems (RWIS) are in use and assist CTDOT with storm monitoring throughout Connecticut. CTDOT plans to add an additional 23 RWIS stations to its RWIS network of stations over the next two to five years. CTDOT should

a. continue sharing weather data with/from surrounding states (MA, NY, RI);
b. share RWIS data and other information about weather events with Connecticut municipalities;
c. consider making RWIS data available to the public via a website; and
d. consider working with other states in the Northeast to provide RWIS data online using a system such as the Meteorological Assimilation Data Ingest System (MADIS) maintained by the Federal Highway Administration and the National Weather Service, as this may benefit municipalities that are located near state borders.

WINTER SEVERITY INDEX (WSI)

CTDOT should develop a WSI. While this is a challenging task, it provides a method to compare winter seasons and develop performance measures. States that have developed a WSI, including Massachusetts and Utah, can be used as references for CTDOT.

ROAD CONDITION INDEX (RCI)

CTDOT should consider developing a RCI that would be available on a regional basis during a winter weather event for state roads. This would allow CTDOT to provide information directly to the public. One of the most important and difficult aspects of this would be the need to keep the information current during a winter weather event. Utah DOT has a RCI that could be used as a guide for CTDOT.

CLEAR ROADS CONSORTIUM

CTDOT should continue their participation in the Clear Roads consortium pooled fund project. Participating in these groups enables CTDOT to be aware of ongoing research and new products. CTDOT should participate in Clear Roads field trials if possible and appropriate.

Equipment

GROUND SPEED CONTROLLERS

The inclusion of ground speed controllers for deicing chemical application on all new equipment purchases should be considered standard practice to ensure that the desired application rates are achieved. Ground speed controllers are installed on virtually all of CTDOT's material spreading equipment, and it is recommended that municipalities do the same.

CALIBRATION OF SPREADERS

The calibration of material spreaders should be performed at least on an annual basis or as required, which is the current practice of CTDOT and many municipalities. Accurate record keeping will be useful for determining if a specific piece of equipment is applying a radically different amount of material than expected. This may be an indication that the spreader needs to be recalibrated. It is also suggested that spreaders should be calibrated two to three times during the winter season, as well as after any repairs are performed.

SALT SLURRY SPREADERS

Salt slurry spreaders have been successful at improving the application of salt materials. CTDOT purchased salt slurry spreaders to test this technology in Connecticut. Initially, the testing involved setting up the equipment to apply the desired amount of material. It is expected that these spreaders will be tested in operation in the winter of 2015/2016.

Similar to the process noted above, an example of a process or steps suggested for implementation of other new technologies is as follows:

- First, demonstrate the product.
- Next, test the product in operation under actual conditions typically experienced.
- Finally, follow with operational implementation and monitoring to assure that the results are those that are expected.

GPS AND MATERIAL DATA LOGGERS

The technology exists to track the location of deicing chemical-spreading vehicles via GPS while at the same time recording spreading equipment settings. This data can be used to develop a very detailed material application tracking system. These types of systems require analysis of the data and can generate a great deal of data depending on how they are configured. Therefore, before implementing this type of system, it is necessary to determine how this data will be managed, as well as how it will be used for monitoring and improving performance, as well as decision making.

MULTI-SECTIONAL PLOWS AND UNDERBODY SCRAPERS

Multi-sectional plows improve plowing performance on uneven roads. Underbody scrapers are useful for maximizing snow removal on roadways with packed snow and ice. These technologies should be considered for plowing operations since plowing is the most environmentally friendly method for snow and ice removal — the more snow and ice that is removed mechanically, the less deicing chemicals needed. Currently, CTDOT uses underbody scrapers on a limited basis, and reportedly underbody scrapers and multi-scetional plows are used by several municipalities.

APPLYING AND VERIFYING APPLICATIONS

Technological improvements that should be considered for winter maintenance operations to maximize deicing chemical application efficiency include:

a. measuring and weighing loads of deicing chemicals and abrasives to accurately track the amount of materials used; and

b. pavement and air temperature sensors for all trucks that can be used for decision making for varying application rates based on current and forecasted conditions.

SUMMARY

Sustainable winter maintenance operations are achieved by balancing the demands of the users, the available budget, and the environment. Chloride-based deicing chemicals will continue to be the most common deicer used for winter highway maintenance operations. While chloride-based deicers are effective at helping transportation agencies remove snow and ice from roadways, which assists in providing the traveling public with safe roadways and mobility as soon as possible following a winter weather event, their use also contributes to increased corrosion of infrastructure and vehicles, as well as possible environmental impacts.

Therefore, under the assumption that safety and mobility of the traveling public are key goals of winter highway maintenance operations, it is necessary for everyone to recognize that minimizing the negative impacts of the use of chemical deicers is a shared responsibility.

- For transportation agencies, this includes achieving the maximum benefit from the least amount of chemical deicer application, and assuring that best practices are utilized for operations.

- For the general public and commercial vehicle owners and operators, this includes washing vehicles after each winter weather event to remove as much deicing chemical as possible; inspecting the undercarriages of vehicles periodically for damage due to corrosion of critical safety components; and having reasonable expectations for the return of roadways to a safe condition following a winter weather event.

As previously noted in this report, the DOTs of the states surveyed for this study are responsible for maintaining different types of roadways, with different levels of service being required. Additionally winter weather events vary from state to state. These factors make state to state comparisons of deicer chemical usage and practices useful only as a frame of reference for use by each state in seeking to continually improve winter maintenance operations. Taking this into consideration, CTDOT's total application of chlorides per lane-mile is typically lower than that of the other surveyed northeastern states.

It is important for CTDOT to continually monitor, review and implement winter highway mainteance best practices including operations, technological advances, and use of improved deicing chemicals to maximize efficiency and reduce adverse effects on infrastructure, vehicles, and the environment while maintaining public safety and mobility.

1.0 BACKGROUND AND INTRODUCTION

1.1 BACKGROUND

In 2005, the Connecticut Academy of Science and Engineering (CASE) conducted a study, *Improving Winter Highway Maintenance: Case Studies for Connecticut's Consideration* [1] on behalf of the Connecticut Department of Transportation (CTDOT) for improving winter highway maintenance. The Connecticut Transportation Institute (CTI) at UConn was engaged by CASE as the research team to conduct the literature-based best practices/case studies review. Following completion of the project in April 2006, CTDOT changed their winter highway maintenance practices to follow the study's recommendations that were based on the best practices identified through the research. This included essentially eliminating the use of sand and using rock salt as the primary treatment for deicing and anti-icing.

Prior to 2006, CTDOT's practice could be characterized as a deicing approach—allowing snow to accumulate on the roads, then plowing the roads while spreading a mixture of sand and salt to provide traction. While this approach was generally effective, it often resulted in "snow pack"—snow and ice that bonded onto the road. Snow pack would often last for many hours, and sometimes days, after the end of a storm event, requiring significant staff labor, large quantities of salt and the use of equipment to remove it.[2]

Starting in the winter of 2006/2007, CTDOT implemented anti-icing to improve the effectiveness of its winter highway maintenance practices. Anti-icing consists of using carefully pre-calibrated equipment to spread salt that has been pre-wetted with chloride-based liquid deicer early in a storm, and as necessary throughout, to prevent the snow and ice from bonding to the road. Anti-icing is a proactive approach to maintaining roads during snow and ice events. It does require using a more technical methodology, with the end result being bare pavement much sooner after a storm has ended. In most situations, the application of sand is not part of this approach to fighting winter storms.[2]

As noted in the 2006 CASE study, winter highway maintenance evolves over time, and CTDOT has recognized the need to periodically evaluate current procedures and identify possible areas for change and improvement.

Recently, concerns have been raised regarding corrosion to vehicles, as well as the impact of the use of salt on highway and bridge infrastructure. As a result, in 2014 the Connecticut General Assembly (CGA) adopted Public Act No 14-199, Section 6 that directed the Commissioner of Transportation to *conduct an analysis of the corrosive effects of chemical road treatments on (1) state snow and ice equipment vehicles, (2) state bridges, highways and other infrastructure, and (3) the environment. Such analysis shall determine the cost of corrosion created by chemical road treatments and shall include an evaluation of alternative road treatment techniques and products, including, but not limited to, the addition of rust inhibitors to current chemical road treatments, and a comparison of costs and effectiveness.*

1.2 INTRODUCTION AND OBJECTIVES

This study was conducted for CTDOT by CASE to address the issues specified in Section 6 of Public Act 14-199, which required the Commissioner to submit a final report (i.e., report on the findings, conclusions and recommendations of the analysis) to the CGA's Transportation Committee. The study provides:

- An update of the study on *Improving Winter Highway Maintenance: CASE Studies for Connecticut's Consideration* (April 2006).
- An examination of a range of winter maintenance areas based on the issues raised in Public Act 14-199, as well as other areas, for use in framing expectations and outcomes of the state's winter highway maintenance operations and practices.
- A summary of past and current practices.
- Recommendations are based on the research conducted, including a literature review, interviews, and presentations to the CASE Study Committee that examined the effects of various deicer materials on vehicles, infrastructure and the environment.

The report includes the following chapters:

- Chapter 2: Overview of Snow and Ice Control Operations on Connecticut Roadways: CTDOT and Municipalities
- Chapter 3: Deicing Chemicals Currently in Use in North America
- Chapter 4: Winter Highway Maintenance Practices in Surrounding States
- Chapter 5: Environmental Impacts and Mitigation of Deicing Chemical Applications for Winter Highway Maintenance
- Chapter 6: Effects of Deicer Corrosion on Infrastructure and Vehicles
- Chapter 7: Best Practices and New Technologies
- Chapter 8: Winter Highway Safety Analysis and Overview of Economic and Societal Impacts
- Chapter 9: Summary of Findings
- Chapter 10: Conclusions and Recommendations

For reference, technical definitions regarding winter highway maintenance terminology are provided in Appendix A: Glossary of Terms. Appendix B provides a listing of CASE Study Committee meetings, including guest speaker presentations.

2.0 OVERVIEW OF SNOW AND ICE CONTROL OPERATIONS ON CONNECTICUT ROADWAYS: CTDOT AND MUNICIPALITIES

CTDOT, like many other state transportation departments, has incorporated the use of various chemical deicers into snow and ice control operations. A report published fourteen years ago for the Colorado Department of Transportation identified several reasons for using chemical deicers for snow and ice control operations.

"*Chemical Deicers are used…:*

- *To keep roads open … by preventing ice and snow from bonding to the pavement*
- *To increase the safety of the driving public by reducing the likelihood of vehicular accidents*
- *To allow for higher traffic speed and traffic volume*
- *To minimize the need for sand, thereby improving air quality*
- *To reduce the time and personnel needed for snow and ice removal*
- *To increase the level of service provided by the Department of Transportation, and*
- *To save on vehicle fuel consumption." [3]*

These reasons for using chemical deicers are as applicable today as then, not only for Colorado, but for Connecticut and all snow-belt states. Effective snow and ice control operations are a common goal for transportation agencies, who need to balance a variety of factors including budgets, personnel, and impacts on the environment, infrastructure and vehicles. Also, the frequency (quantity), severity, and temperature variations of winter weather events are typically taken into consideration to refine localized strategies that are needed to combat such events.

The CTDOT Bureau of Highway Operations, Office of Maintenance, is responsible for response to winter weather events on Connecticut's state-maintained highways and facilities. The 2015 CTDOT report, "An Overview of Snow and Ice Control Operations on State Highways in Connecticut" (Appendix C), provides an overview of basic information on advanced snow and ice control operation practices.[4] While CTDOT is responsible for maintaining 3,734 centerline miles (10,800 lane-miles) of Connecticut's public roads, the remaining 17,339 centerline miles (35,231 lane-miles), or roughly 82% (76% by lane-miles) of the roadway network, is the responsibility of Connecticut's 169 municipalities. The average daily vehicle miles of travel on the entire Connecticut roadway network was 84,770,376 vehicle-miles in 2013.[5] Seventy-six percent of daily vehicle miles of travel occur on the 18% of the roadway network maintained by the state.

Since the winter season of 2006/2007, following the recommendations included in the previous CASE study report [1], CTDOT has employed a snow and ice control practice commonly referred to as "anti-icing." The purpose of anti-icing is to prevent the bonding of snow or ice to the roadway surface. The preventive nature of anti-icing supports higher service level objectives, such as CTDOT's policy that "*The Department shall provide a standard of winter maintenance that provides for the motoring public reasonably safe roads during and after adverse weather conditions throughout the winter season.*" Anti-icing has the potential to improve traffic safety at the lowest possible cost, and with less of an adverse environmental impact.[6]

This strategy contrasts with the traditional deicing strategy that CTDOT employed prior to the 2006/2007 winter season, where an inch or more of snow had to accumulate before plowing and treating began. This frequently led to a compacted snow pack that bonded to the pavement surface. The deicing response at that point required the application of larger quantities of chemicals and abrasives, as well as additional plowing efforts, in order to remove the bonded snow pack.

The following from the 2006 CASE report and other sources helps to define and differentiate anti-icing, deicing, pre-wetting, brine and pre-treating processes.

> ***Anti-icing*** *is a non-mechanical process by which a liquid chemical, usually salt brine, is applied to a roadway prior to or very early in a winter storm event. The chemical is applied to prevent bonding of snow and ice to the pavement surface by lowering the freezing point at which this occurs (Blackburn et al. 2004). It is intended to substantially reduce the amount of effort and material needed to achieve desirable road surface conditions during a winter storm. Salt brine or other chemicals such as calcium chloride ($CaCl_{2)}$ or magnesium chloride ($MgCl_2$) are common materials used in anti-icing. In many cases, calcium chloride or magnesium chloride is used at colder temperatures (lower than the freezing point of the salt brine solution).*[1]
>
> ***Deicing*** *is a strategy by which ice and/or compacted snow is removed from the roadway by either a chemical or mechanical means or a combination of the two. This includes chemical treatments, such as salt, which are applied later in a winter storm and continued past the end of the storm. De-icing generally requires more materials and effort than anti-icing to achieve the same desirable road surface condition (Blackburn et al. 2004).*[1]
>
> ***Pre-wetting*** *is the process by which a liquid chemical (usually salt brine or water) is added to the [solid] salt prior to application to the road. This mixing pre-activates the salt to begin de-icing much faster than non-pre-wetted salt in its solid state (Environment Canada, 2005). Pre-wetting can occur at different points in the application process and different equipment options are used on the trucks. Pre-wetting reduces the amount of bouncing and scattering that takes place when the material hits the roadway. The city of Toronto's Department of Transportation Services states that application of solid crystal salt to the roadway can result in up to 40% of the material being lost in ditches and gutters (Environment Canada, 2005). They also found that pre-wetting reduces the amount of salt needed by 10-20%.*[1]
>
> ***Salt brine*** *is a liquid solution of salt, most commonly sodium chloride and water. Salt brine is relatively commonly used by transportation agencies. In a liquid brine solution, the salt has already been activated, which means that upon contact with the road surface, it is already working to melt snow and ice. A high-speed brine stream is a delivery method which may differ from pre-wetting applications in the mixture and application techniques. In the use of brine, salt is not mixed with water immediately prior to application as it is in pre-wetting, but rather mixed, in most cases, at a central facility, where it is then loaded into a truck equipped with a tank. The trucks are outfitted with spray nozzles that dispense the brine on the roadway. Brine streams are often used as an anti-icing measure. In some locations, large tanker trucks are used in this process.*[1]

Pre-treating is a specific task that is used as part of an anti-icing program. Pre-treating can be the application of either a liquid chemical such as salt brine, a dry solid chemical salt or a pre-wetted solid mixture of chemicals to the pavement surface prior to the start of a winter weather event. Pre-treating is a proactive preventive strategy to decrease the possibility of snow bond, black ice from freezing rain or frost formation on the pavement surfaces.

2.1 CTDOT'S SNOW AND ICE CONTROL OPERATIONS

The material presented in this section of this report is excerpted and/or summarized from CTDOT's report "An Overview of Snow and Ice Control Operations on State Highways in Connecticut" [4] *that is contained in its entirety as Appendix C.*

CTDOT's winter maintenance responsibilities cover a roadway network of over 10,800 lane-miles that are designated into three categories or classes: limited access highways (Class 1); primary routes (Class 2); and secondary/miscellaneous routes (Class 3). These roadway classes are used to define the level of service to be maintained during winter weather events. The winter maintenance service level details that are provided for each class are included on page 2 of Appendix C. In addition, CTDOT is responsible for winter maintenance of commuter parking lots and other state facilities.

It is noted that the general public only observes limited aspects of snow and ice control operations. The elements of a winter maintenance operation include: planning and analysis of plowing routes, acquisition of equipment and materials, annual snow plow operator training, storm tracking and weather prediction, highway condition monitoring, a thorough understanding of when to apply anti-icing or deicing techniques, the maintenance and deployment of a current fleet of 632 plow trucks and other specialized equipment such as loaders and snow blowers, coordination of approximately 200 supplemental contracted plow trucks, and many other activities for preparation, deployment and post-cleanup operations.

The estimated annual winter maintenance budget, typically based on 12 storms per year, is approximately $30 million. Winter weather events are defined by CTDOT as activities and storms. Activities typically last less than six hours and involve less than 50% of the workforce. Storms are of longer duration with more than 50% of the snow and ice control workforce activated. The winter maintenance budget for 2014-2015 winter season was $32.8 million. However, due to the unusually severe winter, actual expenditures for 2014/2015 will exceed $49 million.[7]

CTDOT reported that its winter maintenance strategy was developed to:

- Proactively utilize weather information, anti-icing methods and manpower
- Provide continuous plowing and critical operational support throughout storm events
- Balance effective treatment with public safety, environmental concerns and cost
- Prescribe road treatments, based on expected and actual conditions for the three highway classes

CTDOT's deployment of the anti-icing approach actively utilizes weather information to determine the methods and materials that will be used for road treatment based on specific conditions. These conditions include strategic timing of both treatments and plowing based on storm characteristics, treatment activation times, traffic patterns, and time of day. CTDOT reports that this approach results in both an improved level of service and the efficient use of chemicals.

Truck routing, lane coverage and synchronization of truck formations (e.g., echelon plowing) are planned in advance and practiced. Plow routes are established by each of the four CTDOT maintenance districts based upon traffic volume, mileage and cycle times, and other priorities. The routes are updated annually, as needed. All material spreaders are calibrated prior to the start of the winter season, and validated periodically. Each truck is labeled with the calibration results.

CTDOT's general practice is to apply chemicals at one pass every three hours. However, while not specifically stated in CTDOT's report, operationally, snowfall rates, traffic conditions, and time of day and day of week are taken into consideration. Also, more materials are applied at the beginning and end of events, and prior to rush hours. During heavy snowfall rates, plowing is performed without applying materials. Various plow and blade configurations, spreading patterns and application rates are used as necessary. Trucks contracted by CTDOT are used for plowing only and do not apply chemicals.

In coordination with contracted weather services, CTDOT has divided the state into seven geographic weather zones. Information about an impending winter weather event is provided by these services for decision making purposes. CTDOT also has staff designated as "storm monitors." They serve as central points of contact for incoming winter weather events and coordinators for staffing and equipment information. Storm monitors also collect and disseminate field weather conditions during storms. During major storms, communication is also maintained with the Department of Emergency Services and Public Protection. In severe winter conditions, the governor may activate the Emergency Operations Center. The governor may also declare a travel ban, under extreme conditions. Also, CTDOT discusses and coordinates travel bans with neighboring states, including the Transportation Operations Coordinating Committee (TRANSCOM), a coalition of 16 transportation and public safety agencies in the New York—New Jersey—Connecticut metropolitan region.

CTDOT truck-mounted air and pavement temperature sensors, as well as information from 13 Road Weather Information Systems (RWIS) strategically located throughout Connecticut, are used to collect field data. In addition to pavement surface and subsurface temperatures, the RWIS stations can provide location-specific information on relative humidity, dew points, and current precipitation type. An additional 23 RWIS stations are proposed for installation. Two Highway Operation Centers (Newington and Bridgeport) provide real-time weather observation as well as access to 324 highway traffic cameras. These monitoring operations also communicate with the State Police on any weather-related incidents that occur and apprise the storm monitors and the operation managers of real-time road conditions. To facilitate mobility, traffic signal timing on specific routes is adapted to winter weather conditions to increase capacities during the winter weather event. A CTDOT storm center, located at the department's headquarters in Newington, serves as a center of operations during all winter weather events.

Prior to any anticipated winter weather conditions, to help prevent or minimize unsafe road conditions resulting from frost, freezing rain and snow, CTDOT employs pre-treatment at specific pre-determined locations. These locations include bridge decks, ramps, shaded, and known areas of concern. A detailed decision flowchart provided on page 5 of Appendix C is used to determine when pre-treatment is appropriate. A 23% brine (sodium chloride) solution comprising rock salt (sodium chloride) and water used for pre-treatment is manufactured by CTDOT at centralized department facilities. Upon field application, the brine solution dries on the pavement surface and provides anti-icing treatment for up to five days before an event occurs. It is not applied when temperatures are below 22°F. The amount applied is either 30 or 40 gallons per lane-mile, with air temperatures at approximately 32°F or 22°F, respectively. According to CTDOT, the implementation of pre-treatment using brine solution has aided in the prevention of black ice conditions, and improved mobilization time and efficiency during traditional non-work periods.

During an actual winter weather event, CTDOT's stated goal is to keep snow and ice from bonding to the pavement surface. For most conditions above 20°F, sodium chloride is used, and applied at a rate of 200 pounds per lane-mile, in accordance with a snow and ice guidelines document published by CTDOT in October 2013.[8] A solution of liquid magnesium chloride at 30% by weight with water is used to pre-wet the sodium chloride. Also, during certain circumstances when temperatures are above 25°F, the sodium chloride brine solution may be used for pre-wetting. The solid sodium chloride is pre-wetted at the rate of one gallon per lane-mile during application to help keep the particles on the road, which results in 3.23 pounds of magnesium chloride being applied per lane-mile. Pre-wetting also activates the sodium chloride more quickly, and allows it to melt snow and ice at a lower temperature. Less bounce and scatter on the road surface provides for more effective use of the material applied, and therefore less material is needed. CTDOT reports having used calcium chloride for pre-wetting until 2012, when it was phased out due to supply- and price-related issues and replaced with magnesium chloride, which had previously been piloted by CTDOT with good results.

CTDOT performs post weather event cleanup where necessary with industrial blowers, payloaders and the use of manual labor to clear pavement shoulders, bridges and viaducts, ramps, gore areas, catch basins, signs, low visibility areas, median barriers and sidewalks. After weather events, all equipment is cleaned, checked and repaired as necessary. Periodically, a salt neutralizing agent is applied to all snow and ice equipment.

CTDOT maintains detailed records of material usage for each winter weather event. Chemical material application rates are reviewed to ensure compliance with CTDOT guidelines. Summaries of material used and labor employed during winter weather events (sodium chloride, liquid magnesium chloride solution, person-hours, etc.), are created and summarized by district and/or individual crew. In addition, the budget is tracked, and material supplies are inventoried and re-stocked. Material usage is affected by characteristics of individual storms, such as duration, intensity, wind speed, temperature, time of day, re-freezing, and ice accumulation.

Table 2.1 (Appendix C: Table 3) provides a history of storms, weather activities, total snowfall range, usage of sand, sodium chloride, calcium chloride, magnesium chloride and total chlorides for the winter seasons from 2000/2001 through 2013/2014. This table includes some data that are referred to in other chapters of this report.

TABLE 2.1. ESTIMATED CONNECTICUT WINTER STORM AND CTDOT MATERIAL USE TOTALS: 2001 – 2014 (APPENDIX C, TABLE 3)
NOTE: SHADING FOR SEASON (YEARS) 2000/2001 – 2005/2006 INDICATES SAND/SALT MATERIALS USED, WITH PRIMARILY SALT MATERIALS USED IN THE OTHER YEARS (NOT SHADED)

Season (Years)	Storms (No.)	Activities (No.)**	Total Snow-fall*** (Range, Inches)	Sand (Tons)	Sodium Chloride (Tons)	Calcium Chloride* (Tons)	Magnesium Chloride* (Tons)	Total Chlorides Applied (Tons)
2000/2001	17	11	25-71	307,310	140,850		-	140,850
2001/2002	9	5	5-26	94,260	40,220		-	40,220
2002/2003	16	10	50-98	303,110	140,110		-	140,110
2003/2004	12	9	46-79	225,310	103,820		-	103,820
2004/2005	18	4	51-77	317,130	161,900		-	161,900
2005/2006	11	6	25-62	198,310	107,930		-	107,930
2006/2007	9	6	6-30	6,790	104,760	481	-	105,241
2007/2008	14	10	13-70	2,860	185,000	1,240	-	186,240
2008/2009	13	8	33-58	4,230	179,710	1,492	-	181,202
2009/2010	12	5	22-67	60	131,040	1,333	-	132,373
2010/2011	15	5	52-87	10	179,490	1,092	748	181,330
2011/2012	6	4	9-31	-	62,550	141	422	63,113
2012/2013	11	9	35-74	-	160,930	-	1,727	162,657
2013/2014	17	11	40-62	-	225,170	-	2,341	227,511

Note: All materials applied as solids (sand and sodium chloride) are rounded to the nearest 10 tons; Shaded area indicates seasons prior to deployment of anti-icing practices
*Applied in Solution: $CaCl_2$ (32%) Solution (3.54 lbs/gal); $MgCl_2$ (30%) Solution (3.23 lbs/gal)
** Activities are precipitation events; do not include applications from 're-freeze' events
***Snowfall amounts, as measured at CTDOT Maintenance Facilities

The tallies for storms and activities shown in Table 2.1 do not include isolated weather events such as spot treatments in the case of a possible re-freeze. However, materials used during isolated weather events are included in Table 2.1. Winter seasons have been quite variable over the past 14 years. The number of storms in Connecticut has varied from a low of six to a high of 18 during this period. CTDOT reports that during the winter of 2013/2014 the average storm was 20 hours in duration.

The official winter weather season defined by CTDOT is November 1 – April 30. However, annually CTDOT's winter maintenance activities extend outside this period. During the "off-season," CTDOT performs the following activities:

- Equipment is cleaned and a neutralizing agent is applied
- Snow plowing routes are reviewed for the purposes of optimization and efficiency
- Potentially hazardous trees and brush are removed
- Structures, drainage areas and other roadside obstacles are identified and staked before the next season
- Stockpiles are replenished
- Equipment and supplies are replaced
- New contracts are executed

Operational coordination and oversight are important additional activities required before, during and after winter weather events. CTDOT reports that meetings, both during and after the winter season, post-storm critiques, tailgate talks, weekly status reports on material usage, contractor performance, weather reporting, and equipment performance are typical activities and analyses used to gauge the status of winter operations. In 2006 CTDOT formed a Snow and Ice Control Committee comprising staff members from its bureaus involved with finance, planning, environmental issues, and maintenance. The committee meets monthly to discuss and critique snow- and ice-related issues and concerns, environmental policy and materials. In 2015, CTDOT made the Snow and Ice Control Committee a Standing Committee that will produce an annual report describing the department's activities and deliberations and information from assessing the state-of-the-practice of ice and snow control.

Training and outreach are also important parts of winter maintenance. New as well as experienced workers from CTDOT Maintenance and other areas of CTDOT and Connecticut Department of Energy and Environmental Protection (DEEP) receive classroom and field instruction, including field work area instructions for marking snowplow routes. In addition, numerous educational programs are provided by UConn's Technology Transfer Center for municipalities and CTDOT employees involved with winter maintenance.

State of the art technologies and procedures are reviewed by CTDOT on a continuing basis. CTDOT reports that over the past decade, important improvements to winter highway maintenance have been made in Connecticut. Table 2.2 titled "CTDOT Snow and Ice Control Maturity Chart" (Appendix C: Table 4) delineates the advances made between the period prior to 2006, through 2013/2014 and beyond. The most noteworthy changes include the following:

- Conversion to anti-icing
- Elimination of the use of sand, which occurred gradually between 2006—2011 (See Table 2.1)
- Adoption of pre-treating and pre-wetting practices and strategies
- Installation of additional RWIS sites

- Advancements in equipment (rear discharge chutes, belly scraper blades, composite snowplow blades)
- Data for decision-making, such as temperature sensors in vehicles
- Weather forecasting tools
- Most recently, CTDOT purchased industrial snowblowers, salt slurry generation applicators, deicer applicators for multiple lanes, and is adding more salt brine production facilities

TABLE 2.2. CTDOT SNOW AND ICE CONTROL MATURITY CHART

Prior to 2006	2006 – 2013	2013-2014 Season and Beyond
Strategy: Deicing	**Strategy: Anti-Icing**	**Strategy: Anti-Icing**
• Sand & Sodium Chloride (7:2 Ratio) Rate: 1564 lbs./2-lane mile (LM), (non-multi-lane) • Sodium Chloride Rate: 432 lbs./2-LM	Sodium Chloride Rate: 200 lbs./LM	Sodium Chloride Rate: 200 lbs./LM
CT Patent on Brine Truck Technology; 1979	Programmed Pre-treating at Select Locations: Brine Solution (23% Sodium Chloride); 2007 – 2013	Programmed Pre-treating at Select Locations: Brine Solution (23% Sodium Chloride)
Pre-treating and Brine Application Field Trial; 1997 – 1998	Pre-Wetting: (All Pre-mixed, uninhibited, unless indicated.) • Inhibited Calcium Chloride Solution (32%); 2006 – 2008 • Calcium Chloride Solution (32%); 2008 – 2010 • Calcium Chloride (32%) or Magnesium Chloride Solution 30%); 2010 – 2012 • Magnesium Chloride Solution (30%); 2012 – 2013	Pre-Wetting : 1 gallon Magnesium Chloride Solution/LM; Magnesium Chloride Solution (30% by weight)
First Road Weather Information System (RWIS) installed, Route 2, Lebanon, CT; 1997	Additional RWIS Installed	RWIS Network • 13 Existing RWIS Systems • 23 Additional Proposed
Fleet: • Began installing air and temperature sensors on maintenance vehicles; 1999	Fleet/Facilities: • Acquired Trucks and updated facilities for pretreating; 2006 • Continued to deploy air/pavement temp sensors on vehicles • Trial Rear-Center Vehicle Salt Application Spreader; 2009-2013 • Developed CT Rear Truck-Mounted Discharge Chute; 2012 • Underbody scraper blades, 6 Trucks	Fleet/ Facilities: • Increased salt brine capabilities at various maintenance garages. • Purchased Vehicles Rear-Center Vehicle Salt Application Spreader for use on multi-lane highways • Purchased industrial snow blowers; 2013 • Composite blades • Trial of Salt-Slurry Generation Applicator; 2013 • Purchased three Salt-Slurry Generators

Of the items listed in Table 2.2, pre-treating and pre-wetting have had the most significant impacts on CTDOT's winter maintenance operations. CTDOT reported the following benefits of pre-treating and pre-wetting:

Pre-treating

- Significantly reduces accidents on major river crossings
- Mitigates bonding of snow and ice to pavement
- Provides plow drivers more time at the onset of a storm
- Reduces deicer chemical use
- Promotes bare pavement sooner after winter weather events
- Reduces overall cost of snow and ice control operations

Pre-wetting

- Improves the effectiveness of the use of solid deicers
- Improves activation for melting
- Retains deicing materials on the road
- Reduces the total amount of material used

The conversion to pre-wetting in 2006 necessitated the installation of liquid storage tanks at CTDOT facilities and retro-fitting of all older trucks with saddle tanks and pre-wetting equipment. All new fleet purchases are equipped with pre-wetting equipment.

Initially, during the 2006/2007 and 2007/2008 seasons, the calcium chloride solution used by CTDOT for pre-wetting contained corrosion inhibitors. These inhibitors proved to be problematic. Settling and coagulation occurred in bulk storage and clogging of application nozzles occurred. Additionally, there were concerns about the effect of corrosion inhibitors on the environment due to potential degradation of water quality with an increase of Biochemical Oxygen Demand (BOD) in waterways required for the breakdown of the inhibitors. The effectiveness of the inhibitors for reducing or preventing corrosion was also questioned. As a result, the corrosion inhibitors were eliminated from the calcium chloride product used by CTDOT.

CTDOT reported that a bridge rinsing pilot program was conducted in 2012 on 25 bridge structures that did not span watercourses. The bridges included in this program did not contain lead paint. This project was performed in cooperation with DEEP. CTDOT is considering initiating an additional bridge rinsing program.

Connecticut is a member (along with 28 other states) of a 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. CTDOT maintenance also stays engaged with surrounding states, including New York, Massachusetts and Rhode Island to maintain dialogue with practitioners who have similar winter weather challenges.

Other changes being implemented by CTDOT that could enhance winter maintenance practices include a linear referencing system to provide an ability to spatially link routing and other roadway attribute data for road network management. This will assist in snow plow route optimization. Also, augmenting RWIS with non-intrusive sensor technology has the potential to improve data collection.

As noted in the summary of CTDOT's reference [4]

> *Advancements in technology and knowledge gained from operations and research have improved the state's winter maintenance practices. These include the anti-icing approach, pre-treating and pre-wetting methods, as well as new technologies for improved assessment of road conditions, material placement and fleet operations. CTDOT has adopted advancements and continues to actively seek improved practices to address the complex challenges of winter highway maintenance.*

2.2 MUNICIPAL CHEMICAL DEICER USE AND WINTER MAINTENANCE PRACTICES

Although the primary purpose of this study is an evaluation of winter maintenance activities on state-maintained roads, Connecticut's municipalities were also surveyed to gain insights regarding their winter maintenance practices, since municipalities are responsible for the maintenance of 82% of the state's centerline roadway network miles.[9]

The content of the survey was developed by the research team and reviewed by the CASE Study Committee and CTDOT staff. The survey was conducted electronically using SurveyMonkey®. Each of Connecticut's 169 municipalities were asked to participate in the survey. The municipalities were informed that the responses would remain anonymous so as not to create undo pressure on any given municipality, and to avoid the perception of a competitive or "report card" scenario.

The survey was composed of 24 elements or questions, including standard identifiers and contact information (Appendix D). A primary purpose for conducting the survey was to determine the quantity of deicers (sodium chloride, proprietary deicers, and sand) utilized by the towns during the most recent five winter seasons (2009/2010 through 2013/2014). In addition, the survey was used to identify the winter maintenance equipment and practices used by the towns, including pre-wetting, pre-treating, temperature sensors, ground speed control, the age of equipment fleets and observations on corrosion of equipment.

Sixty-nine municipalities responded to the survey, of which 47 completed at least a portion of the survey in addition to contact information, with 46 of the 47 towns including quantities (tons) of deicers and/or sand used for at least some of the winter seasons as shown on Table 2.3.

As shown in Table 2.3, over 50% of the towns responding to the survey used sand during this five-year period. The number of responding towns using straight sodium chloride declined from 54% to 46% during the first four seasons, and then increased to 56% in 2013/2014. The number of responding towns using treated road salt, which is pre-wetted with magnesium chloride and organic inhibitors increased from 54% in 2009/2010 to 65% in 2010/2011, and remained steady through 2013/2014.

TABLE 2.3. QUANTITIES OF SAND AND DEICER CHEMICALS USED
(REPORTED BY 46 RESPONDING MUNICIPALITIES)

Type of Product	2009/2010		2010/2011		2011/2012		2012/2013		2013/2014	
	% of Towns Report Using	(Tons)	% of Towns Report Using	(Tons)	% of Towns Report Using	(Tons)	% of Towns Report Using	(Tons)	% of Towns Report Using	(Tons)
Sand	52	**46,410**	50	**41,457**	50	**27,412**	50	**37,711**	61	**52,359**
Solid Deicers										
Sodium Chloride (Rock Salt)	54	33,415	52	42,481	48	26,001	46	37,085	56	50,280
Treated Road Salt	54	58,647	65	65,061	65	35,816	65	61,877	65	86,557
Other Non-specified Solid Chloride Deicer	4	1,773	7	3,384	7	1,621	7	3,274	7	4,470
Total Solid Deicers		**93,835**		**110,926**		**63,438**		**102,236**		**141,307**

At least six towns responding to the survey reported using liquid deicers on some occasions for pre-treating or during a winter weather event for anti-icing. Some of these towns reported purchasing quantities of liquid Ice B′ Gone™ or Magic-0™ (Minus Zero) which is a liquid de-icing agent made from a patented blend of magnesium chloride combined with an agricultural by-product of the distilling process (i.e., grain and/or sugar based). However, none of the towns reported using bio-based agricultural by-products exclusively. A couple of towns noted that Ice B′ Gone contains molasses or other organic biodegradable corrosion inhibitors.

Using the 46 town responses, an extrapolation was performed to estimate the amount of solid deicers possibly used by all Connecticut municipalities during each of the past five winter seasons for the state's municipal roadway network. The extrapolation was based on a ratio of the total centerline miles from the responding towns (5,077 miles) to the total centerline miles of all 169 towns (17,339 miles). To obtain the estimated total tons of municipal deicer likely used during each of the five winter seasons, the total deicers reportedly placed by the 46 towns is simply multiplied by the ratio (17,339/5,077) 3.4152.

The results of this analysis are shown in Table 2.4. It should be noted that these values are approximations because of some inconsistencies in reporting by the municipalities that participated in the survey as well as the projection of these values for all 169 towns. Some towns did not have salt and sand data for all five seasons due to recordkeeping or staff turnover. Other towns only estimated the tons of sand and deicers rather than providing actual measurements.

The chloride deicers applied by CTDOT during these same five winter seasons are taken from data shown in Table 2.1 and replicated in Table 2.4 for easy reference and comparison. The estimated total solid deicers used by the state and towns by winter season based on CTDOT-reported data and reported and estimated town data is shown in Table 2.4. These quantities do not include chemical deicer applications on private business parking lots, sidewalks or state parking lots. It is noted that the State of New Hampshire estimated that salt applications on municipal and state roads accounted for 51.6% of salt loads to the environment, whereas another 35% was used for treating parking lots and private roads.[10] For Connecticut, data for treating parking lots and private roads were not available nor estimated for this study. However, based on the New Hampshire analysis, it is possible that the application of chemical deicers and sand materials for parking lots, private roads, sidewalks and state parking lots in Connecticut may be substantial.

TABLE 2.4. ESTIMATE OF TONS OF TOTAL DEICERS USED STATEWIDE DURING FIVE WINTER SEASONS

(NOTE: BLUE SHADING = REPORTED DATA;
RED SHADING = ESTIMATE BASED ON EXTRAPOLATION OF REPORTED DATA)

	2009/2010	2010/2011	2011/2012	2012/2013	2013/2014
46 Survey Towns Reported Solid Deicer Used (tons) (*from bottom line of Table 2.3)*	93,835	110,926	63,438	102,236	141,307
169 Town *Estimate* of Solid Deicer Used (tons)	320,000	379,000	219,000	349,000	483,000
CTDOT Reported *Actual* Deicer Used on State Roads (tons) *(from Table 2.1)*	132,373	181,330	63,113	162,657	227,511
***Estimate* of Total Deicer Used on Connecticut Public Roads (tons)** (*sum of 169 towns plus CTDOT not including parking areas or private use*)	**452,373**	**560,330**	**282,113**	**511,657**	**710,511**

The amount of deicers applied varies significantly from year to year depending upon the severity of each winter and specific winter weather events. For example, the estimated quantity of solid deicing chemicals used in Connecticut in 2013/2014 is approximately 252% of the estimated quantity that was used in 2011/2012.

Figures 2.1 through 2.3 graphically show the amount of solid deicers and sand applied by towns and the state on a per lane-mile basis during the past five winter seasons (2009/2010 – 2013/2014). The ratio of state to municipal roadway network lane-miles is 0.31 (10,800 state lane-miles/35,231 municipal lane-miles).

Figure 2.1 shows a graph of the amount of deicer applied for each winter season per lane-mile based upon the reported amounts used for the roadway network lane-miles for the 46 towns that responded to the survey.

Sand was used by 31 of the 46 responding municipalities with these amounts shown in Figure 2.2.

Figure 2.3 shows the amount of deicer applied per lane-mile for each winter season, and the minimal amount of sand used (no sand used after 2010/2011) during the same period for the state-maintained roadway network by CTDOT.

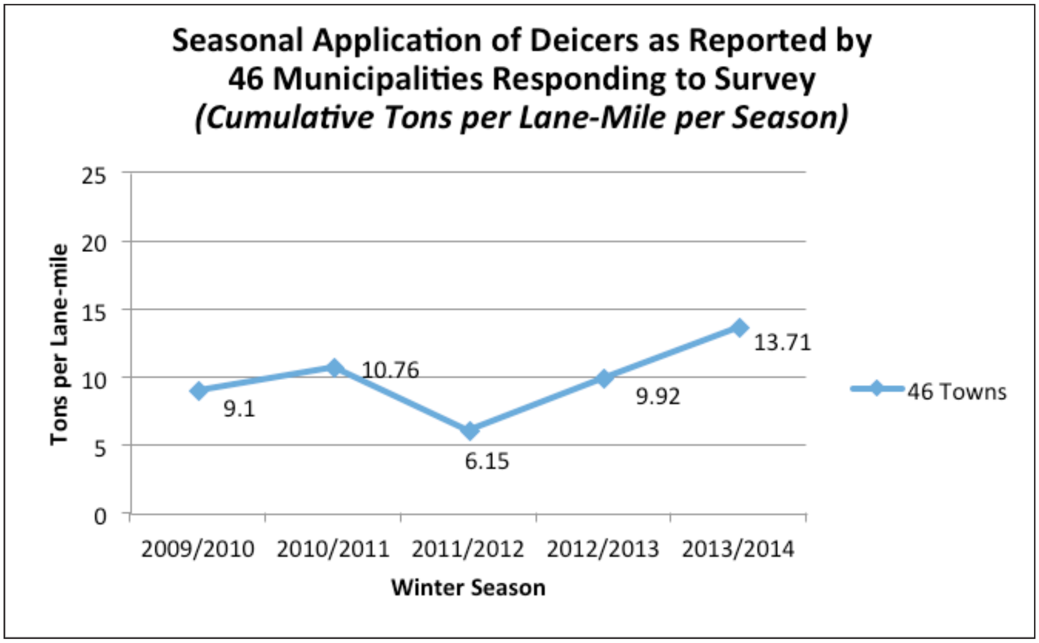


FIGURE 2.1. CUMULATIVE DEICERS APPLIED (TONS PER LANE-MILE)
BY 46 TOWNS FOR FIVE WINTER SEASONS

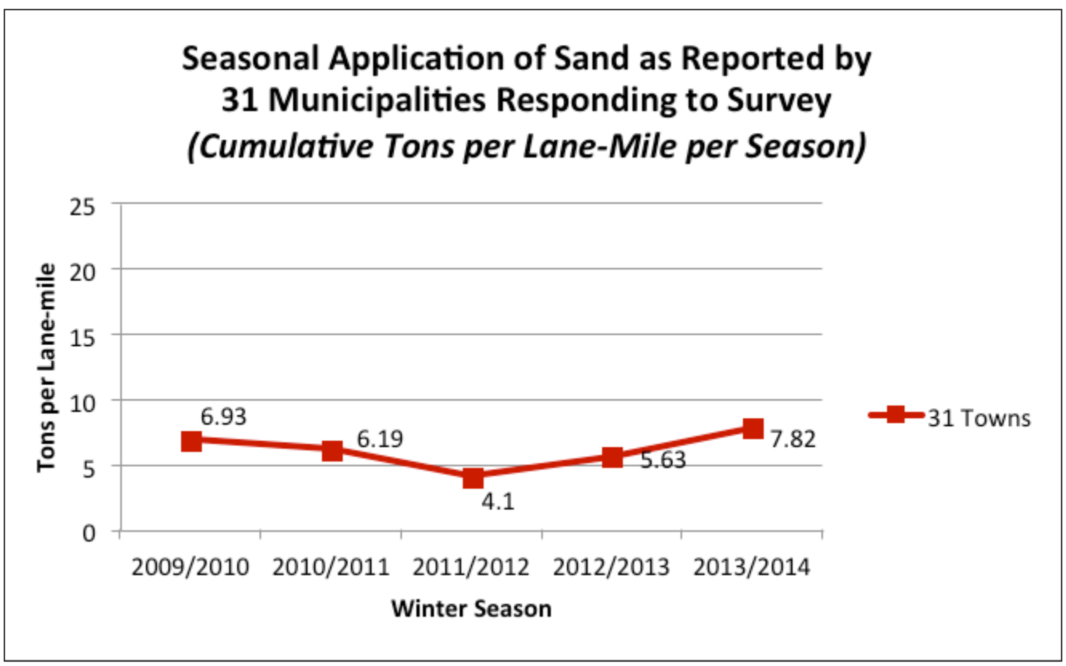


FIGURE 2.2. CUMULATIVE SAND APPLIED PER SEASON (TONS PER LANE-MILE)
BY 31 TOWNS FOR FIVE WINTER SEASONS

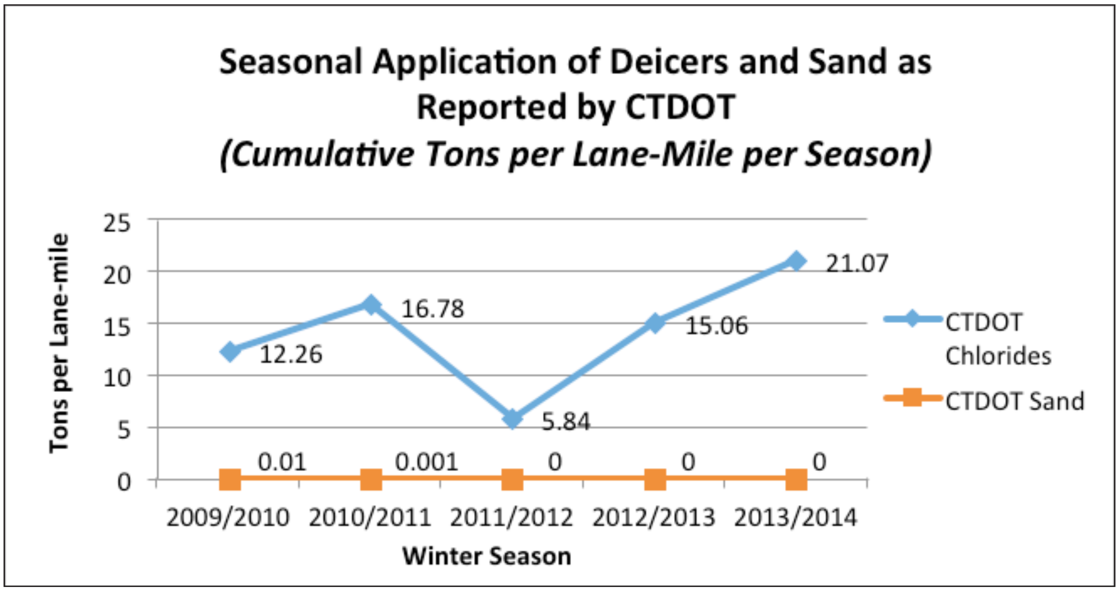


FIGURE 2.3. CUMULATIVE DEICERS AND SAND APPLIED PER SEASON (TONS PER LANE-MILE) BY CTDOT FOR FIVE WINTER SEASONS

Figures 2.1 and 2.3 show that for the period referenced CTDOT applied approximately an average of 43% more deicer per lane mile as compared on an annual basis than municipalities (based on the data provided by municipalities that responded to the survey) for each winter season. This occurs for a number of reasons.

- Municipalities use sand in addition to chemical deicers for snow and ice control, whereas CTDOT does not use sand.
- CTDOT-maintained roadways are generally wider, with full shoulders.
- Many more state roadways are multi-laned and median-divided as compared to town roadways.
- Greater traffic volumes and higher posted speed limits on state roads generally necessitate a higher level of service during winter weather events. CTDOT's policy is to apply 200 lbs./per lane-mile of sodium chloride per pass.

The significant difference in the quantity of sand that was applied per lane-mile to roadways by the towns that reported their usage and CTDOT during the last five winter seasons is shown in Figures 2.2 and 2.3. This difference is due primarily to a CTDOT policy that eliminated the use of sand after 2006, except for special conditions. Based on a review of typical material costs, a cost analysis should be expected to indicate that the elimination of the use of sand provides cost savings for the purchase, application, and storage of materials, and cleanup during the spring and summer. It is noted that since deicers weigh less than sand and the application rates (pounds per mile) for straight deicers are generally lower than for the sand-salt mixture, plow routes can be expanded, thereby reducing the need to reload trucks as often.

Additionally, based on analysis of data provided in Table 2.1, the average annual quantity of chlorides used by CTDOT for the eight-year period (2006-07 thru 2013-14) following it's elimination of the use of sand is approximately 34% higher than for the prior six-year period (2000-01 thru 2005-06). (This percentage does not take into consideration variations in the winter weather between the periods. It is strictly a numerical difference.) Also, a comparison of the same periods shows that the average annual quantity of total materials used (sand and chlorides) by CTDOT was approximately 56% lower for the period when only chlorides were used (2006-07 thru 2013-14) as compared to the period when sand and chlorides were used (2000-01 thru 2005-06.)

While CTDOT does not use proprietary salt products (treated road salt), several municipalities do use these products. In many cases, towns use treated road salt products because they do not have the facilities for producing brine for pre-treating roadways or for storing materials that can be used for pre-wetting solid deicer chemicals. Treated road salt products, depending on the specific product used by towns, can potentially contain much higher levels of magnesium chloride and calcium chloride than products used by CTDOT.

CTDOT uses sodium chloride that is pre-wetted on the dispensing truck at the time of application with a 30% liquid magnesium chloride solution using the salt dispensing chute. It is fairly easy to estimate the amount of magnesium chloride that is applied on roads from the known capacity of the truck's onboard holding tanks. For example, in the 2013/2014 winter season, a total of 2,341 tons of magnesium chloride was used, which is 1% of the total tonnage of deicers used by CTDOT (see Table 2.1). When the CTDOT pre-wets sodium chloride on its application trucks, the amount of magnesium chloride liquid solution (30% by weight) used is one gallon per 200 pounds of sodium chloride.

The treated road salt products purchased by municipalities are pre-coated with magnesium chloride liquid. As an example, the specification for treated road salt that is used by towns comprising the Capitol Region Council of Governments (CRCOG) calls for a liquid magnesium chloride and organic based inhibitor to be applied at eight gallons per ton of solid deicer, with the solid material being at least 91% sodium chloride by weight. The remaining 9% may comprise liquid magnesium chloride, calcium chloride, water or other additives such as molasses [11]

Additional information provided by municipalities that responded to the survey is summarized as follows:

- Pre-wetting and Pre-Treating
    - 22% of responding towns pre-wet solid deicers
    - 13% pre-treat roads with liquid deicers
    - 56% pre-treat roads with solids before the start of a winter weather event

- Equipment Corrosion
    - 32.2% of responding towns noted equipment corrosion has increased none or very little in recent years

  - 25.6% noted equipment corrosion has increased moderately in recent years
  - 41.9% of responses noted equipment corrosion has increased significantly in recent years

- Winter Maintenance Equipment
  - The average reported municipal winter maintenance equipment fleet age is 10 years
  - The average reported expected winter maintenance equipment service life is 14 years
  - Frequency of calibration of deicer spreading equipment: <1/yr 5%; annual 78%; >1/yr 17%
  - 63% of responding towns use ground speed control for spreading sand or deicers
  - 34% of municipal winter maintenance vehicles are equipped with ground surface temperature sensors

3.0 DEICING CHEMICALS CURRENTLY IN USE IN NORTH AMERICA

This section of the report is based primarily upon a literature review. It describes and assesses the chemicals that are currently used for deicing in the United States and Canada (Table 3.1). A few of these chemical deicers have had only limited use on highways, but more extensive use at airports. Also, some chemicals have had more use in Europe than in North America. This section also discusses the use of abrasives for snow and ice control.

In this report, deicing chemicals are often referred to as “deicers.” Some deicers can be used for anti-icing treatments, as well as for deicing activities to break the bond that occurs between the roadway and snow/ice during a winter storm. Deicing, plowing, spreading of abrasives and other methods comprise strategies used for winter maintenance to enhance the condition of highways prior to, during, and after snow and ice events.

A deicing chemical may be available and used in either a liquid or solid state or both. Liquid deicers have two advantages: they limit the amount of bounce and scatter during application, thereby decreasing the amount of material that needs to be applied, and they do not require moisture to be able to start working. However, typically liquid deicers are used in solution with a lower concentration of the deicing chemical than in its solid state, so they cannot melt as much snow and ice as solids. Liquid deicers also may run off of roads with significant cross-slopes or super-elevations. Solid deicers will tend to bounce and scatter during application, which may result in some of the product ending up in the shoulder or off the road. Since deicers applied in a solid state have a much higher chemical concentration than liquid deicers, they will be effective for a longer period of time. A disadvantage of solid deicers is that they require water to begin the melting process.

The effectiveness of chemicals used for deicing is based on their ability to lower the freezing point of water. The eutectic temperature for products used in snow and ice control is the lowest freezing point depression of water that can be achieved at an optimum concentration. Chlorides are inorganic chemicals while all other chemicals described in this section used for melting snow and ice are organic. One major disadvantage of organic deicers is that during decomposition, the microbes degrading the chemicals require a great deal of oxygen—otherwise known as Biological Oxygen Demand (BOD). BOD can rapidly deplete the dissolved oxygen in bodies of water, thereby negatively impacting aquatic wildlife. Generally abrasives used in Connecticut are sands that contain very little organic matter, but they do not melt snow and ice.

There are at least 250 proprietary deicer products, as well. Most of these products contain a combination of the same common chemical deicers that are described individually below, plus corrosion inhibitors, anti-caking additives, and colorants. Due to the large number of products and constant reformulation and remarketing, it is not practicable to list and discuss all of the proprietary deicer products in this report. However, a few of these products that are commonly used by several Connecticut municipalities are discussed in this chapter.

Appendix E includes a summary of the advantages and disadvantages of products typically used for snow and ice control.

Table 3.1. Estimated Costs for Materials Potentially Used for Roadway Winter Maintenance Activities

MATERIAL TYPE	DESCRIPTION	ESTIMATED COST	COST SOURCE
Abrasives	Sand or Grit	$25 - $50/ton	Estimated
Chlorides	Sodium chloride or rock salt, halite; also the usual component for salt brine	$66.78-79.66/ton	DAS Contract 14PSX0170 9/24/14
	Magnesium chloride; in 30% magnesium chloride concentration solution	$0.69-0.76/gallon solution	DAS Contract 13PSX0180 10/16/13
	Calcium chloride; solid or in 32% calcium chloride concentration solution	> $160/ton solid $0.76-0.88/gallon solution	DAS Contract 13PSX0180 10/16/13
	Potassium Chloride		Not Located
Acetates	Calcium magnesium acetate (CMA)	~ $1,800/ton	NHDOT 9/27/14 [10]
	Sodium acetate	>$ 1,900/ton	DAS Contract 13PSX0183 10/2013
	Potassium acetate in 50% water solution	$5.50/gallon solution	NHDOT 9/27/14 [10]
Formates	Sodium formate	~$1,700/ton	Seneca Sales & Supply, Erie PA 3/4/15 [12]
	Potassium formate	(A)	Not Located
Carbohydrate/Agricultural or Organic By-products (ABPs)	Corn syrup, corn steeps, other corn derivatives • (2% corn syrup) **FreezGuard Cl Plus**	(B) $1.07-1.127/gal	Omaha, NE Bid 8/27/14 [13]
	De-sugared or sugared beet juice • (55% beets) **Beet 55** • (20% beet juice sugar) **Ice Bite**	(B) $1.116/gal $1.60/gal	Omaha, NE Bid 8/27/14[13] NYS Thruway 2013 [14]
	Molasses	(B)	Not Located
	Brewers/distillers by-product	(B)	Not Located
Urea/Carbamide		$360/ton	Chemical Solutions Inc. (phone quote) 3/4/15 [15]
Propylene Glycol		$5.00/gal (premixed 25-50%) $17.75/gal (concentrate)	Chem World (website quote) 3/4/15 [16]
Proprietary Products (C)		(C)	
Treated Road Salts (D)	Ice B Gone® Magic	$81.82-86.56/ton	CRCOG bid 611 6/26/14 [11]
	Clearlane® Enhanced Deicer	$76.47-98.89/ton	CRCOG bid 611 6/26/14 [11]
	FireRock® Caliber M2000 w/Shield AP	$91.20/ton	CRCOG bid 611 6/26/14 [11]

(A) There is very little pricing information available on this product; it is primarily used in European countries
(B) Pricing of these products varies greatly; they are typically blended with chlorides to improve their melting capabilities
(C) There are potentially as many as 250 proprietary products to choose from. Price will vary by product
(D) Treated road salt = Sodium chloride + anti-caking agents + magnesium chloride (liquid) + organic based performance enhancer

3.1 ABRASIVES

Abrasives are defined as *sand or grit-sized aggregates* (e.g., sieved bank run gravel, incinerator ash or mining slag "clinker," and cinders). Abrasives can be effective for traction under certain conditions. According to the National Cooperative Highway Research Program (NCHRP) Report 526, Snow and Ice Control: Guidelines for Materials and Methods, "the primary function of abrasives is to provide temporary traction (friction) improvement on snow/ice surfaces." [17] However, most abrasives are readily removed from the roadway with the passage of traffic, making them ineffective shortly after application.

It is estimated that more than 50% of abrasives that are placed on roadways are not recovered. For this reason, as well as many of the disadvantages cited below, there has been a continuing decline in the use of abrasives throughout the United States, including Connecticut. CTDOT discontinued using its standard sand and salt mix (7:2 Ratio) in 2006, around the time of the previous CASE study.[1] At that time, it was apparent that many other states were transitioning away from the use of abrasives due to the cost of removal and lack of effectiveness as a deicer. As discussed in chapter 2, abrasives are still in use in several municipalities in Connecticut, and for emergency situations by CTDOT.

Advantages

- Provides traction on ice
- Provides color delineation for travel lanes for public assurance that a product has been applied to the road surface
- Use is independent of temperature

Disadvantages

- Does not lower freezing/melting point of ice. (However, dark color of abrasive may help accelerate ice melting with sunshine)
- Traffic causes migration of abrasives from roadways into ditches off roadways
- Can increase water turbidity and be detrimental to the surrounding environment
- Clogs drainage systems and accumulates in runoff areas, including streams and ponds
- Can increase air pollution
- Clumps together and freezes when damp, unless mixed with deicers
- Absorbs and impedes effectiveness of deicers
- Causes buildup on road shoulder areas precluding sheet flow runoff, often requiring additional road maintenance
- Material must be removed in the spring and summer at significant cost, both time and expense.

3.2 CHLORIDES

There are three prevalent chloride chemical deicers (or salts) in use in the United States and Canada: sodium chloride, magnesium chloride, and calcium chloride. Potassium chloride, only effective from approximately 20°F and higher, has also been used as a deicer, but due to its high cost compared to other chlorides, its use has nearly disappeared.

The effectiveness of chlorides is based on factors such as relative humidity, concentration on the roadway surface, speed of chemical reaction with moisture, and temperature. Chlorides require moisture to initiate the melting/deicing process. Such moisture can be absorbed from the atmosphere, from snow and ice melt, or most effectively by using a pre-wetting agent.

3.2.1 Sodium Chloride

Similar to the state of the practice in 2006, sodium chloride, also known as rock salt, or road salt, is by far the most commonly used and traditionally least expensive deicer chemical. The Salt Institute estimates the total annual amount of sodium chloride used in the United States to be approximately 22 million tons.[18] According to a Duke University report, this is more than 100 times the quantity used in 1940.[19] Sodium chloride is used in a solid crystal form that can be applied dry or by adding water to the crystals at the time of application, and as a brine that is typically 20%-23% sodium chloride and water solution. CTDOT has utilized sodium chloride brine as an anti-icing pre-treatment since the winter season of 2006/2007, and also uses small quantities of calcium or magnesium chloride solution in combination with solid sodium chloride for deicing.[8] Technical documentation and the experience of many transportation agencies indicate that sodium chloride effectively melts snow or ice from approximately 15°F to 20°F and higher. At temperatures below this range, a much higher application rate is required in order for sodium chloride to be effective.[20] Sodium chloride can prevent bonding of snow to the pavement surface, and assist in its removal by plowing.

Advantages

- Least expensive deicer for Connecticut and most states
- Most prevalent deicer product (i.e., widespread availability)
- Causes less deterioration of Portland Cement Concrete (PCC) compared to other chlorides [21]
- Can be used for anti-icing, deicing and pre-wetting
- Not as hygroscopic (moisture absorbing) as other chlorides at moderate levels of relative humidity (which is beneficial for storage of solid form, and for pretreating roads with brine)

Disadvantages

- Detrimental to surrounding environment (particularly for degradation of water quality in surface and groundwater; buildup in soil; and negative effects on some types of roadside vegetation from surface runoff, aerosols from vehicle spray, and wind)

- Not very effective as a deicer when ambient temperatures are below 15°F, unless large quantities are used
- Accelerates corrosion of metals including steel reinforcement in pavements and bridge structures
- Corrosive to some motor vehicle components
- Attracts animals to roadsides, which can be a safety hazard to motorists and animals
- Can raise sodium levels in drinking water, adversely affecting human health

3.2.2 Magnesium Chloride

Under low temperature conditions, magnesium chloride is more effective for deicing than sodium chloride. The generally accepted minimum temperature for magnesium chloride to be effective as a deicer or for anti-icing based on experience of DOTs is approximately 5°F. It is most commonly used in solid form in Canadian provinces as well as western and northern states (e.g., northern Michigan, Minnesota, Colorado and Idaho). These regions tend to have more winter storms per season than Connecticut, with precipitation often occurring at temperatures below 20°F. Starting around 1995, Colorado was one of the first states to use solid magnesium chloride for deicing.

CTDOT has never used solid magnesium chloride, but since 2009 has used liquid magnesium chloride solution for pre-wetting solid sodium chloride applications, particularly during mid-winter when the pavement temperature is below 25°F. CTDOT's typical application is one gallon of 30% (by weight) magnesium chloride solution to 200 pounds of solid sodium chloride. Magnesium chloride is not used as a liquid application for pre-treating roadways by CTDOT.[8] Many of Connecticut's municipalities use various forms of magnesium chloride in combination with sodium chloride on local streets.

Magnesium chloride theoretically can cause more severe concrete deterioration than sodium chloride.[21] This deterioration occurs as a result of a reaction between the magnesium ions and calcium silicate hydrate (C-S-H). Magnesium reacts with the C-S-H present in cement paste to produce magnesium silicate hydrate (M-S-H). Unlike C-S-H, M-S-H does not have properties of a cement and it provides no strength to the concrete.[21]

Advantages

- Lowers the freezing/melting point of water to approximately 5°F
- Even at low temperatures solid magnesium chloride works quickly due to its ability to absorb moisture from the atmosphere (hygroscopic nature)
- Can be used for anti-icing, deicing and pre-wetting

Disadvantages

- Causes corrosion of metals including steel reinforcement in pavements and bridge structures

- Corrosive to some motor vehicle components
- Can accelerate corrosion (compared to sodium chloride) due to moisture absorption (magnesium chloride absorbs moisture from the atmosphere when relative humidity is as low as 30%, [22] which keeps surfaces to which it has adhered wet)
- Moisture attraction can make a pavement wet and potentially slick when the magnesium chloride is at a high enough concentration, such as when it is used for anti-icing (pre-treating)
- Magnesium ions can cause more severe concrete deterioration than sodium chloride [21]
- In solid form, straight magnesium chloride is considerably more expensive than sodium chloride (> $150/ton)

3.2.3 Calcium Chloride

Many states have used or currently use calcium chloride for deicing and/or anti-icing. In most states, calcium chloride is used on a much smaller scale than sodium chloride or magnesium chloride. The most significant factor about calcium chloride is that it can lower the freezing/melting temperature of water to approximately -60°F, when it is at its optimum concentration of 30% with water.[22] It is considered less harmful to plants and roadside vegetation than sodium chloride.

CTDOT has not used solid calcium chloride, but has reported using a liquid calcium chloride solution as an agent for pre-wetting solid sodium chloride during six winter seasons (2006/2007 through 2011/2012). Liquid calcium chloride was also initially used by CTDOT for anti-icing tests in 2007. However, since 2012, calcium chloride has not been used by CTDOT, at least partially due to cost and availability as compared with magnesium chloride.

Advantages

- Works effectively to lower the freezing/melting point of water to at least 25°F below that of sodium chloride and water
- Works quickly due to its hygroscopic nature
- Can be used for deicing, as brine for pre-wetting or anti-icing
- Releases heat (exothermic) when applied as a solid and combines with moisture

Disadvantages

- The calcium in calcium chloride can react with other elements in concrete and cause deterioration of the concrete
- Can cause corrosion of metals in reinforced concrete for roads and bridges
- Corrosive to some motor vehicle components

- Considerably more expensive than sodium chloride (> $160/ton)
- Its ability to attract moisture can make a pavement wet and potentially slick when present in high concentrations such as when it is used in anti-icing pretreatments.
- It is so hygroscopic that as a solid it eventually dissolves in the water it absorbs; this property is called deliquescence. To prevent this, it must be kept in tightly-sealed containers.

3.3 ACETATES

Acetates for deicing are generally manufactured through the reaction of acetic acid and other compounds. Three of the acetate-based deicers in use in North America are described: calcium magnesium acetate, sodium acetate, and potassium acetate.

3.3.1 Calcium Magnesium Acetate (CMA)

CMA was first developed in the late 1970s and touted as an environmentally safe alternative to chloride deicers. It is usually manufactured from dolomite limestone and acetic acid (vinegar). In 1991, Congress asked the US Department of Transportation (DOT) to sponsor a study examining the total costs of salt and CMA, including the direct cost of application and indirect costs to the environment, infrastructure, and motor vehicles. The most significant impediment to the use of CMA was its cost, which was 20 times that of sodium chloride.[23] Much of the cost of CMA is the result of producing high-concentration acetic acid.

CMA appears to be more effective at keeping water from freezing than for melting snow or ice. It changes the physical properties of water and ice/snow in a different way than chlorides, which makes for better traction in snow and for easier removal of the snow from the pavement, but not melting.[23]

Advantages

- Low toxicity to plants
- Biodegradable
- Main ingredient, dolomitic lime is abundant throughout the United States
- Does not cause corrosion to most metals
- Low toxicity to fish
- Assists in prevention of surface water re-freezing
- Reduces snow crystal tendency to stick together

Disadvantages

- Only effective above 20°F
- Can potentially lower dissolved oxygen concentrations in soils and receiving waters, [24]

- Cost is at least 20 times that of sodium chloride (> $1,500/ton) [10]
- Uses large quantities of energy in its production process (i.e., greater life cycle cost)
- Due to its lower density and greater quantity needed (by mass) to be effective, CMA requires more storage space than chlorides [23]
- Requires a higher application rate than salts
- Can cause deterioration of concrete due to calcium's chemical reaction with cement
- Does not ionize as readily as sodium chloride, slowing initial reaction time, and therefore, is less successful than sodium chloride in melting snow and ice accumulations (particularly fluffy, dry snow)

Additional Discussion on CMA

The following paragraphs are taken directly from the 1991 Transportation Research Board report, *Highway Deicing – Comparing Salt and Calcium Magnesium Acetate*.[23]

> *In the selective and experimental situations in which it [CMA] has been used, it has often performed acceptably, although generally not in the same manner and not quite as effectively or consistently as salt. Compared with salt, it is slower acting and less effective at lower temperatures [below 23°F] and in freezing rain, drier snowstorms, and light traffic. The timing of application is more critical than for salt. If application is delayed, its deicing performance is notably reduced. CMA is usually applied in greater quantities (by weight) than is salt – usually by 20 percent or more – though specific quantities vary by storm and user. Because of its lower density and greater volume requirements, CMA may require substantially more truck capacity and enclosed storage space (60 percent or more) than salt, especially for more general use.*
>
> *Because CMA is slower acting than salt and does not always perform as well in light traffic, freezing rain, and dry and cold storm conditions, its widespread use could present significant operational difficulties to highway agencies.*
>
> *CMA is therefore one of many options available to highway agencies to mitigate salt's adverse effects, and its use and acceptance is likely to depend in large part on the progress made in other mitigation areas.*

An additional, more recent study on the comparison of CMA with sodium chloride and salt brine was conducted by the American Society of Civil Engineers during 2013.[25] The results of their work *"conclusively show that CMA, which has been widely touted as an environmentally preferable, if more expensive, alternative to chloride-based treatments, has considerably higher environmental impacts over its entire life-cycle. Most of these burdens are associated with the upstream production processes required to generate the CMA. The salt-based treatments consume considerably less water, energy, and generate fewer greenhouse gases and biochemical oxygen demand in receiving waters. Applying the chloride chemicals as brine rather than in the dry form results in important reductions in all environmental impacts over the entire life-cycle"*.[25]

3.3.2 Sodium Acetate

Sodium acetate works as a road deicer in temperatures as low as approximately 0°F. [26] Sodium acetate is approved for use by the Federal Aviation Administration, and is currently used on runways at Connecticut's airports, including Bradley International Airport. Commercial formulations available for sale contain 1% of an unspecified corrosion inhibitor. These formulas also are pelletized for easier handling and dust reduction, and are generally used in solid form. It also can be pre-wetted with liquid potassium acetate (see discussion below) when being applied.

Advantages

- Exothermic (i.e., gives off heat when reacting with water) which aids in melting of snow and ice and helps prevent melted snow from re-freezing
- Non-toxic (used in food and medical products)
- Biodegradable
- Generally non-corrosive to vehicles, bridges and utilities, which is especially critical for use in connection with aircraft operations and electronic runway lighting
- Lowers the freezing point of water to 0°F

Disadvantages

- Much more expensive than sodium chloride (>$ 1,900/ton)
- May cause eye or skin irritation in solid form
- Inhalation of dust during handling may cause respiratory tract irritation and coughing
- May be corrosive to galvanized steel, zinc and brass
- Quantities could become limited if selected for wider use such as on roadways
- Decomposition can reduce dissolved oxygen in bodies of water

3.3.3 Potassium Acetate

Potassium acetate has recently been primarily used as a deicer at airports and in automated bridge deck liquid anti-icing systems, and reportedly was used in South Dakota and Utah as a deicer for highways prior to 2003. Potassium acetate is produced by the reaction of acetic acid with potassium carbonate (one of the groups of salts commercially known as potash).

A commercial form of liquid potassium acetate, containing a 50% concentration by weight plus corrosion inhibitors, has been used as a pre-wetting agent with dry salt or as a straight chemical deicer application. Potassium acetate costs roughly 25 times more than sodium chloride, [10] but lowers the freezing point of water to approximately -75°F.[6] Due to its high cost, but ability to substantially lower the freezing point of water, it is primarily useful as a pre-wetting agent with other chemical deicers. If it were used as a straight anti-icing application at 50 gallons/lane-mile, it would cost approximately $275 per lane-mile. In comparison, sodium chloride at 200 lbs./lane-mile costs less than $10 per lane-mile. In a laboratory test at the University of Nebraska, potassium acetate outperformed all other deicers in the quantity of ice that it melts at 20°F.[20] Potassium acetate is biodegradable and for the most part considered non-corrosive to metals. Because it lowers the freezing point, when mixed with other salts, it can reduce the amount of those salts required during a storm. Potassium acetate is an ingredient in several commercial non-chloride proprietary products, as well.

Advantages

- Low toxicity to fish, mammals and vegetation
- Biodegradable
- Biodegrades at low temperatures, and thus produces a relatively low increase in BOD during spring thaw when temperatures rise
- Generally non-corrosive to vehicles, bridges and utilities
- Melts snow and ice twice as fast as sodium chloride at 20°F [3] and unlike most chlorides is active below 0°F
- Lowers the freezing point of water to -75°F at specific concentrations
- Meets FAA approved specifications

Disadvantages

- Corrosive to stainless steel
- Expensive compared to sodium chloride ($2,000/ton; $5.50/gallon at 50% concentration)
- May cause gel-like precipitate when mixed with sodium chloride for pre-wetting [20]
- Decomposition can reduce dissolved oxygen in bodies of water
- Dry compound is combustible so it is typically sold in liquid form for highway uses

3.4 FORMATES

A formate is a salt or ester of formic acid. Some formates have demonstrated deicing properties comparable to sodium chloride. Two formates that have been primarily used in Scandinavia, sodium formate and potassium formate, are discussed here.

3.4.1 Sodium Formate

Sodium formate can be prepared in the laboratory by neutralizing formic acid with sodium carbonate. It can also be obtained by reacting chloroform with an alcoholic solution of sodium hydroxide. Sodium formate can be used to reduce the amount of chloride used in winter maintenance operations, but sodium in drinking water could still be an issue or concern [28] as it is with sodium chloride. The freezing-point curve of sodium formate is similar to that of sodium chloride — as low as 7°F.[29] Sodium formate has been used on airport runways.

Advantages

- Relatively non-toxic
- Similar deicing characteristics to sodium chloride

Disadvantages

- Very limited usage experience in the United States — possibly at some airports
- Data pertaining to a sodium acetate /sodium formate-based deicer suggests that during the spring thaw runoff, short periods of oxygen depletion in receiving waters may occur, with potential danger in warmer weather (Bang and Johnston, 1998) [30]

3.4.2 Potassium Formate

Potassium formate is the potassium salt derived from formic acid. According to a paper by Hellsten [31] multiple studies have found that potassium formate does not cause undesirable changes in the groundwater chemistry, owing to biodegradation in topsoil. An aquifer scale study on the fate of potassium formate [32] found it to be easily biodegraded at low temperatures (28°F to 43°F) in soil microcosms, whereas chloride ions from the deicing products used in previous winters had accumulated in the aquifer.[30] Specifically, from one of the Hellsten studies, the following was concluded:

> *Potassium formate was used to deice a stretch of a highway in Finland. It was concluded that the use of potassium formate can potentially help diminish the negative impacts of road winter deicing on groundwater without jeopardizing traffic safety.*[32]

A study on the use of potassium formate in Norway found that to achieve an equivalent penetration hardness of compressed snow, only half the amount of solution content is needed when using a potassium formate solution instead of a sodium chloride solution. Another way to state this is that compressed snow that was saturated with a potassium formate solution was softer than the other solutes. It was only about 75% as hard as snow mixed with sodium chloride solution.[33]

However, little published information was found on the use of potassium formate for deicing in North America.

Advantages

- Makes snow softer and less sticky
- May be less detrimental to the environment than sodium chloride

Disadvantages

- May be corrosive to electrical connectors
- Not used very extensively in the United States
- Limited information is available about this deicer
- Decomposition can reduce dissolved oxygen in bodies of water

3.5 CARBOHYDRATES/AGRICULTURAL OR ORGANIC BYPRODUCTS

Bio-based byproducts are derived from the fermentation and processing of beet juice, molasses, wine, beer, grains, corn, cheese and other agricultural products. These byproducts are generally noncorrosive, but offer limited deicer potential. These products can be very expensive if used alone; however, they are frequently mixed with other common deicers to assist in lowering the freezing point of water and to inhibit corrosivity. Sand and salt treated with byproducts such as a beet juice derivative can adhere to roadways, reducing bounce and scatter and thus, the amount of material that needs to be applied.

According to an EPA report, *"These products are biodegradable and are safer for roadside vegetation than sodium chloride. Communities are still gaining experience with these "eco-friendly" alternatives; additional research and experience with these and other alternatives are needed."*[24] One concern with using bio-based byproducts is oxygen depletion. The organic materials of byproducts when broken down may cause temporary anaerobic soil conditions as well as oxygen depletion in surface waters.[34]

Some locations where beet juice has been used include Missouri, the New York State Thruway, North Dakota, Ohio, Sag Harbor NY, and Washington DC [35] and [36].

Advantages

- Enhances performance of other deicers when mixed with them, allowing for potentially less deicer use per mile, which can reduce the amount of chlorides released into the environment
- Helps sodium chloride "stick" to the road, (i.e., less bounce and scatter)
- Dark color assists melting in sunlight
- Dark color provides for color delineation of travel lanes during snowy conditions

Disadvantages

- Sticky when handling and applying
- Expensive
- Does not have significant ice melting capacity when used alone

- The organic contents of byproducts when broken down may cause temporary anaerobic soil conditions as well as oxygen depletion in surface waters
- Stickiness could cause chlorides (such as sodium chloride and magnesium chloride) to adhere to metals for longer periods of time.

3.6 UREA

Urea, also known as carbamide, is a chemical found in most fertilizer formulas. It is 46% nitrogen. It is manufactured from ammonia and carbon dioxide or from natural gas. According to the website Meltsnow.com, urea is the 14th highest volume chemical produced in the United States.[37] However, nitrogen can be a problem when used in winter maintenance applications. When used in excess, products with urea can damage vegetation. As this compound dissolves, it releases nitrogen into the water, accelerating the growth of algae blooms and further cutting off the oxygen to other beneficial and economically significant aquatic organisms (i.e., fish). This leads to “dead zones,” where there is no dissolved oxygen to support life.[38]

Due to its low corrosivity, but high expense, urea’s use as a deicer typically has been at airports only. Urea has a practical minimum working temperature of around 25F. Urea is not considered highly effective as a deicer below 25°F, and is used less often than it was several years ago.[37]

Advantages

- Non-corrosive to steel reinforcement
- Fertilizes plants

Disadvantages

- Is not very effective as a deicer below 25°F
- Can cause sinus respiratory and eye irritation
- Corrosive to some metals
- Can burn (damage) vegetation in high quantities
- Urea, by itself, has a high BOD and decreases the oxygen available to aquatic organisms
- Costs approximately 500% as much as sodium chloride

3.7 PROPYLENE GLYCOL

Propylene glycol, also known as 1,2-propanediol, can reduce the freezing point of water to as low as -76°F, depending on dilution.[39] This characteristic makes this deicer attractive to airports in extreme temperature conditions and for application to aircraft during conditions when in-flight aircraft icing is expected. Propylene glycol is essentially non-toxic (however, the closely related ethylene glycol is moderately toxic to humans and many animals). It is biodegradable, non-corrosive to metals, non-flammable and easy to handle.[39] On a consumer level, propylene glycol is used in some automotive windshield deicers, and is a common food preservative.

Propylene glycol is known to have a high BOD requirement during degradation in surface waters. The use of propylene glycol for roadway snow and ice control has not been deemed practical due to its cost, which is estimated to be $17.75/gallon in concentrated form ($5.99/gallon in solution). Therefore, it has rarely been used for this purpose.[40]

Advantages

- Non-toxic
- Biodegradable
- Non-corrosive to metals
- Works at very low temperatures
- Safe for handling

Disadvantages

- Expensive
- Depletes oxygen in waters which can adversely affect aquatic life

3.8 PROPRIETARY DEICER PRODUCTS

Proprietary deicer products have become common over the past 25 years. Many, if not most, of these products have been developed using the primary chloride deicers (i.e., sodium chloride, magnesium chloride and calcium chloride) and water (and in some cases colorants) with additives that will make the product:

- spreadable (anti-caking materials such as ferrocyanides, or sodium gluconate);
- stickier (carbohydrates such as molasses, beet juice, distillers condensed solids, or corn sugars) which may be both beneficial and detrimental as these product will hold the deicing chemical on the roadway, as well as vehicle surfaces; or
- less corrosive (corrosion inhibitors such as carbohydrates).

The Pacific Northwest Snowfighters Association (PNS) has identified and tested over 100 products that fall under 12 categories (Appendix F).

Since the purpose of this study is to address winter maintenance in Connecticut, the discussion of the proprietary products in this report focuses primarily on those that are used by municipalities in Connecticut. CTDOT has not used proprietary mixes to-date. Some of these products are called “treated road salts” and are available under a special purchasing contract maintained by the Capitol Region Purchasing Council of the Capitol Region Council of Governments (CRCOG) by the 38 member towns or by any other town that is willing to pay a nominal participation fee. In CRCOG's bid specification, treated road salts are defined as sodium chloride treated with liquid magnesium chloride/organic-based performance enhancer (LMC/OBPE). Within the CRCOG bid specification, it states that the purpose and intent of using treated road salts is to *"reduce corrosiveness, improve low temperature performance, reduce bounce and scatter, prevent clumping and sand pile re-freezing, and enhance flowability."* [41] Because of changes in the marketplace as well as potential bidders, the availability, including the possibility of reformulation, of some proprietary products will change from year to year.[11]

As of November 2014, approximately 100 municipalities and school systems were participating members of the purchasing council. For 2014/2015, there were 49 members who anticipated ordering approximately 200,000 tons of treated road salt through this contract, valued at approximately $16 million. The treated road salt materials included in the 2014/2015 contract included Ice B Gone®Magic, Clearlane® Enhanced Deicer, and FireRock® Caliber M2000 with Shield AP. The companies providing these products included: Morton Salt, Cargill Deicing Technology and American Rock Salt Co. LLC, respectively. Detailed information about these products is available on vendor websites and in the CRCOG contract #611.[41]

Advantages

- Performance at low temperatures (due to presence of magnesium chloride)
- 70% less corrosive to steel (per PNS test as stated by manufacturers) than plain sodium chloride (due to the inclusion of corrosion inhibitors)
- Less bounce and scatter (due to presence of water and biodegradable additives)
- Potential lower total use of sodium chloride as a result of faster and lower temperature melting capabilities

Disadvantages

- Degradation of Portland Cement Concrete (PCC) is possible in the presence of magnesium chloride (magnesium ions cause more severe concrete deterioration than other constituents of common deicing chemicals) [21]
- Detrimental to surrounding environment (particularly for degradation of water quality in surface and groundwater; buildup in soil; and negative effects on roadside vegetation from surface runoff, aerosols from vehicle spray, and wind) due to presence of sodium chloride
- Products containing sodium chloride attract animals to roadsides, which can be a safety hazard to motorists
- Products containing sodium chloride can raise sodium levels in drinking water, adversely affecting human health

3.9 ADDITIONAL DISCUSSION AND COMPARISON OF DEICERS

All deicer products work by lowering the freezing point of water. While the eutectic temperature (the lowest temperature at which a product will depress the freeze point when the product is at the optimum ratio of chemical to water) provides the lowest freeze point, there are other factors that impact a deicing chemical's effectiveness. These factors may actually be more important than the eutectic temperature, as it is not usually possible to have the ideal chemical to water combinations when applying these products to roadways.

Another important factor for consideration of chemical deicers is the rate of melting, or quantity of snow/ice melted per unit of time. This factor is directly related to ambient air and pavement surface temperatures. For example, at 30°F, one pound of sodium chloride will theoretically melt 46.3 lbs. of ice in 5 minutes. At 15°F the same pound of sodium chloride can only melt 6.3 lbs. of ice, and it would take an hour.[42]

For the three chloride products, calcium chloride is considered best able to work at extremely low temperatures, followed by magnesium chloride, then sodium chloride. All three chlorides are hygroscopic, meaning that they will absorb water from the atmosphere within certain relative humidity levels. Magnesium chloride will attract moisture at a relative humidity of 32% or higher, at any temperature. Calcium chloride will absorb moisture when the humidity is 42% or higher between 0°F and 32°F, and at even lower humidity levels at temperatures above freezing. For sodium chloride, the relative humidity needed for moisture absorption is much higher, at approximately 75%.[6] The significance of the absorption factor is that any residual salts on roads or bridges will act as a deicer whenever referenced humidity levels exist, or moisture is present. This also means that these chlorides can be corrosive to metals under the same conditions, with the sodium chloride being less corrosive in typically drier conditions than the others.

Sodium chloride remains the primary chloride deicer and anti-icer of choice by CTDOT, as many of Connecticut's winter storms occur when temperatures are above 20°F (with recent exceptions being the unusually cold winters of 2013/2014 and 2014/2015).

An additional attribute that varies for deicing products is their exothermic (ability to give off heat during a chemical reaction with water) or endothermic (ability to absorb heat during a chemical reaction with water) properties. Table 3.1 contains a summary of the general attributes of the more common deicer products, such as eutectic temperature, whether a product is exothermic/endothermic, and whether the product was found from the literature to be most prevalently used as a solid deicer, liquid deicer, as a pre-wetting agent, and/or for anti-icing purposes. Only those chemicals deemed viable for potential use on Connecticut's roadway network are included in Table 3.2.

Table 3.2. General Properties and Uses of Deicers
(for Deicers Identified in this Study that Appear Most Viable for Use in Connecticut)

Deicer Type	Optimum Eutectic Temperature (°F) (1)	**Percent** Concentration at Eutectic Temperature (1)	Minimum Practical Effective Temperature (°F) (2)	Exothermic (EX) Endothermic (EN)	Applied in Solid Form (3)(4)	Applied in Liquid Form (Typical Concentration)	Used for Pre-wetting: (P) Anti-icing: (A) Deicing: (D)		
Abrasives (sand, grit, etc.)	n/a	n/a	n/a	n/a	**X**	n/a			**D**
Sodium Chloride	**-5.8**	**23.3%**	**15**	EN	**X**	x (23%)	**P**	**A**	**D**
Magnesium Chloride	**-28**	**21.6**	**5**	EX	x	**X** (32%)	**P**	**A**	**D**
Calcium Chloride	**-60**	**29.8**	**-10**	EX	x	**X** (30%)	**P**	**A**	**D**
Calcium Magnesium Acetate	**-17.5**	**32.5**	**20**	EX	x	**X**		**A**	**D**
Sodium Acetate	**-7**	**27**	**0**	EX	**X**			**A**	**D**
Potassium Acetate	**-76**	**49**	**-25**			**X** (50%)	**P**	**A**	

(1) *SOURCE: REFERENCE [40]*

(2) AVERAGE PRACTICAL EFFECTIVE TEMPERATURE BASED ON REVIEW OF MULTIPLE SOURCES

(3) x = MINOR USE

(4) **X** = MAJOR USE

4.0 WINTER MAINTENANCE PRACTICES IN SURROUNDING STATES

Available winter maintenance data for the past five seasons allow for a comparison of winter maintenance practices with surrounding states including the New England states, and New York and New Jersey. Topics include: extent of state road networks, types and quantities of winter maintenance deicing materials used, winter maintenance equipment, and weather data resources.

4.1 BACKGROUND INFORMATION ABOUT EIGHT STATES: NEW ENGLAND STATES, AND NEW YORK AND NEW JERSEY

Table 4.1 provides roadway mileage, vehicle miles of travel, vehicle registrations, and population and land area data for the eight states that were chosen for comparison of winter maintenance practices. Specifically, Table 4.1 contains total public lane-miles of roads (which includes municipal, and for some states, county roads); actual lane-miles that are the responsibility of each state DOT for winter maintenance; annual total statewide vehicle miles travelled (VMT) (2012); total registered vehicles (2012); state population (2011); and land area in square miles (excluding water bodies).

Table 4.1. Roadway Mileage, Vehicle Registrations, VMT and Land Area of the New England States, and New York and New Jersey
(Sorted by State DOT Lane-Mile Responsibility — Column B)

State	(A) Public Lane-miles (2012) [1]	(B) Actual State DOT Lane-Miles (state is responsible for and has provided tonnage of materials used (5-Year Average)	(C) Annual State-wide Vehicle-Miles-Travelled (VMT) (millions) (2012) [1]	(D) Number of Registered Vehicles (2012) [1]	(E) Total Population (2011) [1]	(F) Total Land Area (sq-mi)[1]
New York	242,624	35,839	128,221	10,448,743	19,576,125	47,214
Massachusetts	76,742	15,453	55,940	4,949,859	6,645,303	7,840
Connecticut	**45,659**	**10,800**	**31,270**	**2,706,459**	**3,591,765**	**4,845**
New Hampshire	33,167	9,035	12,894	1,302,441	1,321,617	8,968
New Jersey	85,394	8,496	74,225	7,911,474	8,867,749	7,417
Maine	46,982	8,298	14,199	1,180,092	1,328,501	30,862
Vermont	29,351	7,845	7,216	606,941	625,953	9,250
Rhode Island	13,658	3,300	7,806	854,359	1,050,304	1,045
TOTAL	**573,577**	**99,066**	**331,771**	**29,960,368**	**43,007,317**	**117,441**

NOTE:
1. (Source: Reference [43])

Some of these states are considerably more rural than others, and a correlation between size (land area) and population does not exist. New York, however, is the largest in land area and also the most populous, primarily due to New York City. Maine ranks second in land area and only the fifth in population. Vermont is the least populated and third largest in land area. Connecticut ranks seventh in land area and fourth in population.

Interestingly, when comparing lane-miles for winter maintenance, the state DOTs in Connecticut, Maine, New Hampshire, Vermont and New Jersey all have similarly sized state road networks to maintain, ranging from 7,845 lane-miles (NJDOT) to 10,800 lane-miles (CTDOT). However, the traffic levels—VMT—are much different, reflecting the more urban character of some states (Connecticut, New Jersey) and the large size of others (New Hampshire, Maine).

Each of the DOTs (Agency of Transportation (AOT) in the case of Vermont) in the eight states was contacted to obtain information about winter maintenance practices. Each DOT was asked to provide quantities in tons or gallons for deicers and abrasives, staffing levels for winter maintenance, number of weather stations (RWIS), and plows and equipment for the most recent five winter seasons (2009/2010 – 2013/2014). Tables 4.2 and 4.4 provide information supplied by the DOTs that is summarized by using an average of the five winters, except in the case of RWIS, where the most current year only is used for reporting the number of RWIS sites.

4.2 DEICING MATERIALS USED BY EIGHT STATE DOTS

It is interesting in Table 4.2 to note the variety of products, or more importantly, combinations of products, that the surveyed states are using, as each state attempts to optimize winter maintenance operations. The selection of products and strategies used for effective winter maintenance operations needs to be based on a variety of factors, as each winter weather event produces varying types of precipitation, in varying intensities, and a wide range of temperatures. Also, DOTs in each of the surveyed states have responsibilities for maintaining different types of roadways with different levels of service being required. Even for winter weather events that only involve snow, the snow varies from storm to storm in its density, moisture content, depth, stickiness and other attributes. The amount of winter precipitation varies considerably from state to state during each year, as well. These factors make direct comparisons of deicer chemical usage and practices useful only as a frame of reference for each state's use in analyzing its winter highway maintenance practices in an effort to benefit from the experience of others.

Not surprisingly, due to its cost and availability, the most commonly used solid winter deicing chemical continues to be sodium chloride (rock salt). Commonly used liquid deicing chemicals are salt brine (sodium chloride) and magnesium chloride solution. Also, all states except Maine reported using liquid calcium chloride solution during some of the previous five years, although Connecticut and Massachusetts have been phasing out its use. Maine, New Hampshire and Vermont use liquid Ice B'Gone, which contains magnesium chloride and biodegradable corrosion inhibitors. Small quantities of treated road salt and agricultural by-products, such as beet juice, were reported in use only by New York State DOT.

Table 4.2 shows that four liquid products comprise the primary products used for pretreating and pre-wetting, as well as anti-icing. These products include salt brine (23% sodium chloride and water), liquid magnesium chloride solution (30% magnesium chloride and water), liquid calcium chloride solution (32% calcium chloride and water) and Ice B Gone. These four liquid products used in the eight surveyed states, in order of the product listed above, comprised 56%, 24%, 15% and 5% respectively, of the total number of gallons of liquid deicers used by the DOTs. Some states—Maine, Massachusetts and New Hampshire in particular—have been using blends of the above liquid products, as well.

Table 4.2. Reported Five-year Average (2009/2010 – 2013/2014) Use of Deicer Chemicals and Abrasives from Transportation Agencies in the New England States, New York and New Jersey

Row Label		(I) New York NYSDOT	(II) Massachusetts MassDOT	(III) Connecticut CTDOT	(IV) New Hampshire NHDOT	(V) New Jersey NJDOT	(VI) Maine MaineDOT	(VII) Vermont VTrans	(VIII) Rhode Island RIDOT
A	Solid Sodium Chloride (tons)	*791,200*	*429,323*	***151,836***	*157,223*	*262,531*	*103,084*	*99,949*	*92,180*
B	Liquid Brine (Sodium Chloride and water) (gal)	630,350 *(a)*		***260,700 (a)***		532,459 *(a)*	501,081 *(a)*	*1,648,328*	*9,500*
C	Liquid Brine (85%) and Liquid Magnesium Chloride (15%) mix (gal)		~400,000 *(a,d)*						
D	Liquid Magnesium Chloride Solution (gal)	*172,540*	*865,500*	***648,688***					*39,820*
E	Liquid Ice B'Gone (straight)(gal)				*7,580*		109,328	147,097	
F	Liquid Ice B'Gone and Brine Blend (30:70)(gal)						*292,056 (b)*		
FF	Liquid Ice B'Gone and Brine Blend (20:80)(gal)				*43,360 (b)*				
G	Solid Calcium Chloride (tons)		846.2		27.3		1.6		
H	Solid Premix(4:1) (Sodium Chloride: Calcium Chloride) (tons)		4,231 *(2) (a,g)*						
I	Liquid Calcium Chloride Solution (gal)	*43,775*		***289,985***	*22,873*	*769,953*		*11,085*	*21,320*
J	Solid Treated Salt (tons)	36,296							
K	Liquid Agricultural By-Products (gal)	310				*Yes (3)*			
L	Sand or Abrasives (tons)	10,560	20,365	**14**	58,893 *(1)*	752	10,920	4,840	21,600
	References for data	*Ref.[44] NYSDOT 2015*	*Ref.[45] MassDOT 2015*	***Ref. [4] CTDOT***	*Ref.[46] NHDOT 2015*	*Ref. [47] NJDOT 2015*	*Ref [48] MaineDOT 2015*	*Ref.[49] VTrans 2015*	*Ref. [50] RIDOT 2015*

NOTES:
(1) Converted from cubic yards reported by NHDOT
(2) MA – pre-mix –- mixed at a ratio 4 parts dry Sodium Chloride to 1 part dry Calcium Chloride by weight
(3) Amount not recorded
(a): Made from sodium chloride – Row A; (b): Brine portion made from sodium chloride – Row A; (a, d): Made from sodium chloride – Row A and magnesium chloride – Row D; (a, g): Made from sodium chloride – Row A and calcium chloride – Row G

Another way to present estimates of the amount of deicing materials used is to convert all the reported liquid products to solid chlorides, and then sum and combine this total with the quantity of solid deicers used to identify a grand total of tons of chloride solids applied per year. This calculation is provided in Table 4.3. As shown in Table 4.2, the result of this analysis is presented as a five-year average for each state surveyed. The calculation is relatively simple for the states that use straight magnesium chloride with 30% solids dissolved in water, but is somewhat more challenging for the proprietary products: Ice B'Gone liquid and solid treated salts. The assumptions made in the analysis are as follows:

1. Magnesium chloride per gallon is 30% by weight and weighs 3.23 lbs.
2. Calcium chloride per gallon is 32% by weight and weighs 3.54 lbs.
3. Sodium chloride per gallon is 23.3% by weight and weighs 2.26 lbs.
4. Ice B'Gone I, (based on an MSDS sheet for the product) has an assumed quantity of 55% (5.76 lbs.) of magnesium chloride per gallon.
5. Treated salts were primarily sodium chloride and were counted only as sodium chloride.

From Table 4.3 it can be determined that in the eight surveyed state DOTs, approximately 2.1 million combined tons of chlorides, including both solids and weight of chlorides in liquids, were applied on average per year for deicing and anti-icing during each of the past five winters. Interestingly, the chlorides that are calculated from the liquids represent only 0.5% of the total chlorides placed by the DOTs. In other words, 99.5% of the total amount of chlorides applied in the eight state DOTs were in solid form. Sodium chloride accounts for 99.9% by weight of the solid chlorides that were applied by these states.

The converted tonnage of magnesium chloride from liquids used in the surveyed states is 3,935 tons per year, which represents less than 0.2% of the total chlorides applied. At 2,927 tons, calcium chloride (sum of solid and weight of calcium chloride in liquids) represents another approximate 0.1% of the total chlorides applied annually. This indicates that the amount of magnesium chloride and calcium chloride applied on state-maintained roadways by the eight surveyed states over the past five years is less than 0.33%, extremely small in comparison to the amount of sodium chloride that was used within the region.

A comparison of CTDOT with the DOTs of the other seven states surveyed based on a five-year annual average indicates:

- CTDOT is the third lowest user in total tons of deicer per lane-mile, only slightly more than MaineDOT and VTrans.
- The three highest state DOT chemical deicer users in total tons of deicers per lane-mile averaged approximately twice as much deicer per lane-mile as CTDOT in the past five winters.
- CTDOT is the lowest user of sand on a per lane-mile basis, using virtually no sand during the past 5 years.
- CTDOT is the second largest user of liquid deicers of the eight states, with VTrans using the most. On a per lane-mile basis, CTDOT is the third largest user of liquid deicers, behind VTrans and NJDOT.

Based on this comparative analysis, it is summarized that CTDOT is a comparatively low user of total deicers overall and a high user of liquid deicers. This indicates that CTDOT is proactive in implementing anti-icing techniques and best practices for pretreating and pre-wetting.

TABLE 4.3. SUMMARY OF FIVE-YEAR (2009/2010 – 2013/2014) AVERAGE USE OF CHLORIDES AND ABRASIVES BY STATE TRANSPORTATION AGENCIES IN NEW ENGLAND, NEW YORK AND NEW JERSEY

Row Label	Product Used per Year	(I) NYSDOT	(II) MassDOT	*(III) CTDOT*	(IV) NHDOT	(V) NJDOT	(VI) MaineDOT	(VII) VTrans	(VIII) RIDOT	TOTAL *(Sum of columns (I) through (VIII))*
M	**Gallons of All Liquid Chloride Deicers Applied**	846,975	1,265,500	*1,199,373*	73,813	1,302,412	902,465	1,806,510	70,640	**7,506,988**
N1	Sodium Chloride (from Solid and Liquid) (tons)	827,496	429,323	*151,836*	157,223	262,531	103,084	101,812	92,191	**2,125,495**
N2	Calcium Chloride (from Solid and Liquid) (tons)	77	846	*513*	68	1,363	2	20	38	**2,927**
N3	Magnesium Chloride (from Liquid) (tons)	279	1,495	*1,048*	59	0	567	424	64	**3,935**
O	**Total Tons of All Chlorides (N1+N2+N3)**	827,852	431,664	*153,397*	157,350	263,894	103,653	102,255	92,293	**2,132,357**
P	Chlorides Applied as Liquids Only (tons)	1,068	1,879	*1,856*	100	1,964	1,133	2,306	113	**10,419**
Q	**Percent of Chlorides Applied as Liquids Only (P/O)**	**0.13%**	**0.44%**	***1.24%***	**0.06%**	**0.74%**	**1.09%**	**2.26%**	**0.12%**	**N/A**
R	# of DOT Maintained Lane-miles	35,839	15,453	*10,800*	9,035	8,496	8,298	7,845	3,300	**99,066**
S	Gallons of All Liquid Chloride Deicers Applied per Lane-mile (M/R)	23.6	81.9	*111.1*	8.2	153.3	108.8	230.3	21.4	**N/A**
T	Tons of Liquid Chloride Applied per Lane-mile (P/R)	0.0298	0.122	*0.172*	0.011	0.2285	0.137	0.294	0.034	**N/A**
U	Tons of Total Chlorides Applied per Lane-mile (O/R)	23.10	27.93	*14.20*	17.42	31.06	12.49	13.03	27.97	**N/A**
V	Tons of Sand or Abrasives Applied per Lane-mile	0.29	1.32	*0.001*	6.52	0.09	1.32	0.62	6.55	**N/A**

Other statistics showing Connecticut and CTDOT relative to the reported totals for the eight surveyed states based on the five-year average (2009/2010 – 2013/2014) include the following:

Percent of total eight-state population residing in Connecticut (2011) *(Table 4.1; Column E)*	8.4%
Percent of total VMT (on all public roads, not just those maintained by DOT) in Connecticut (2012) *(Table 4.1; Column C)*	9.4%
Percent of total eight-state DOT lane-miles maintained by CTDOT *(Table 4.1; Column B)*	10.9%
Percent of total eight-state quantity (tons) of sodium chloride (solid, plus liquid converted to tons) used by CTDOT *(Table 4.3; Row N1)*	7.1%
Percent of total eight-state quantity (gallons) of sodium chloride brine used by CTDOT *(Table 4.2; Row B)*	6.6%
Percent of total eight-state quantity of liquid magnesium chloride, plus proprietary products containing magnesium chloride (quantity calculated from gallons of solution to tons of magnesium chloride) used by CTDOT *(Table 4.3; Row N3)*	26.6%
Percent of total eight-state quantity of calcium chloride in tons used by CTDOT *(Table 4.3; Row N2) (*See Note)*	17.5%
Percent of total quantity (tons) eight-state total all chlorides applied by CTDOT *(Table 4.3; Row O)*	7.2%
*Note: CTDOT only utilized calcium chloride in solution while other agencies used it as either a solution or a solid	

It is noted that even though the quantity of liquid in gallons used by CTDOT is relatively high compared with the other surveyed states, the total use of magnesium chloride and calcium chloride is extremely low relative to the amount of sodium chloride used. Specifically, the amount of magnesium chloride and calcium chloride combined is only 1.0% of CTDOT's total chloride use with the remainder being sodium chloride.

4.3 EQUIPMENT AND STAFFING FOR WINTER MAINTENANCE IN EIGHT STATE DOTS

Table 4.4 provides information reported by the eight surveyed DOTs about winter maintenance equipment, staffing and RWIS stations. Due to each state's policies and practices, it is difficult and unfair to directly compare staffing levels and equipment. While some states have been gearing up for snow and ice control with use of internal DOT resources, others have gone through various phases of privatization and outsourcing. One statistic that is somewhat outside the realm of political policy would be the total available snowplows (contracted, DOT-owned and standby) per lane-mile maintained. The inverse, and more easily understood, statistic is the lane-miles of road coverage per available snowplow. The yearly and five-year average for this statistic is shown in Table 4.5. Based on this analysis, at 17.1 lane-miles per snowplow, CTDOT ranks approximately in the mid-range of the surveyed states.

TABLE 4.4. REPORTED FIVE-YEAR AVERAGE (2009/2010 – 2013/2014) USE OF EQUIPMENT AND STAFFING FROM TRANSPORTATION AGENCIES IN THE NEW ENGLAND STATES, NEW YORK AND NEW JERSEY

Item	(I) New York NYSDOT	(II) Massachusetts MassDOT	(III) Connecticut CTDOT	(IV) New Hampshire NHDOT	(V) New Jersey NJDOT	(VI) Maine MDOT	(VII) Vermont VTrans	(VIII) Rhode Island RIDOT
State Plow Trucks(#)	1,429	194	**632**	311	539 *(3)*	425	250 +25 *(2)*	116
Contractor plow trucks (#)	0	3500	**205**	387	1800 *(3)*	~20	0	213
Staff (#)	3,745	670	**1100**	661	600 *(3)*	900	375	147
2013 RWIS Sites (#)*(1)*	39	34	**13**	19	40	9	22	13
References for Data	*Ref. [44] NYSDOT 2015*	*Ref. [45] MassDOT 2015*	***Ref. [4] CTDOT***	*Ref. [46] NHDOT 2015*	*Ref. [47] NJDOT 2015*	*Ref. [48] MaineDOT 2015*	*Ref. [49] VTrans 2015*	*Ref. [50] RIDOT 2015*

NOTES:
(1) Number of RWIS sites existing in 2013 only are reported in this row
(2) Vermont AOT: 25 trucks are on standby
(3) Only 2013/2014 data were available from NJDOT

TABLE 4.5. DOT LANE-MILE RESPONSIBILITY PER AVAILABLE SNOWPLOW

State	Lane-miles per snowplow 2009	Lane-miles per snowplow 2010	Lane-miles per snowplow 2011	Lane-miles per snowplow 2012	Lane-miles per snowplow 2013	5-Year Average Lane-miles of coverage per available snowplow
New York	25.4	25.2	25.1	25.0	25.0	25.2
Massachusetts	4.0	4.3	4.2	4.2	4.2	4.2
Connecticut	**17.1**	**17.1**	**17.1**	**17.1**	**17.1**	**17.1**
New Hampshire	13.0	12.8	13.1	12.9	12.8	12.9
New Jersey	3.9	3.9	3.9	3.9	3.9	3.9
Maine	18.6	18.7	18.7	18.7	18.7	18.7
Vermont	31.3	31.4	31.4	31.4	31.5	31.4
Rhode Island	8.3	11.0	11.8	7.2	15.5	10.8

Additionally, the number of RWIS stations within each state is referenced. The number of RWIS stations does not convey the full extent of weather data availability for each state, as some states have older RWIS stations that may not be fully functional, and others have newer systems with greater capabilities. The data reported in Table 4.4 provide only the total reported number of RWIS by state in 2013. The types of data collected by RWIS sites and how it should be used for winter highway maintenance operations decision making were not specifically requested in the state survey.

It was reported in reference [4] and previously in Section 2 of this report that CTDOT has plans for supplementing its 13 existing RWIS with 23 additional stations over the next few years. Based on the data reported, Rhode Island and New Jersey had the most RWIS sites per lane-mile. Following installation of the additional planned stations, Connecticut will have a similar number of stations installed per lane-mile as compared to these two states.

5.0 ENVIRONMENTAL IMPACTS AND MITIGATION OF DEICING CHEMICAL APPLICATIONS FOR WINTER HIGHWAY MAINTENANCE

Numerous reports have detailed the environmental impacts of chloride-based road salts to soils, surface waters, groundwater, and biology.[51][25][53] This section summarizes the general findings of these reports, updates them with recent references from the primary literature, and discusses the potential impacts of alternative deicing chemicals. In addition, the long-term environmental trends are noted, and the structural and regulatory actions applied to mitigate environmental impacts are discussed.

5.1 ENVIRONMENTAL IMPACTS OF CHLORIDE SALTS

The environmental impacts of chloride salts depend on the pathways and rates at which chloride salts travel through the environments adjacent to roads (Figure 1). Aerosols (traffic-generated road sprays) containing chloride salts can transport short distances, potentially impacting roadside wetlands, soils or vegetation. Surface runoff can travel greater distances, impacting lakes and streams. Also, groundwater can travel greater distances, and the rate at which it travels and its impacts depend on whether the aquifer is shallow or deep. The transport of chloride salts through any of these pathways depends on numerous physical and chemical characteristics of the landscapes (soil texture, vegetation density, slopes, etc.), the chloride salt (e.g., chemical form, particle size), and the weather conditions (e.g., temperature, humidity, rainfall volumes and rates). Specific environmental impacts are detailed in the following paragraphs and summarized in Table 5.1.

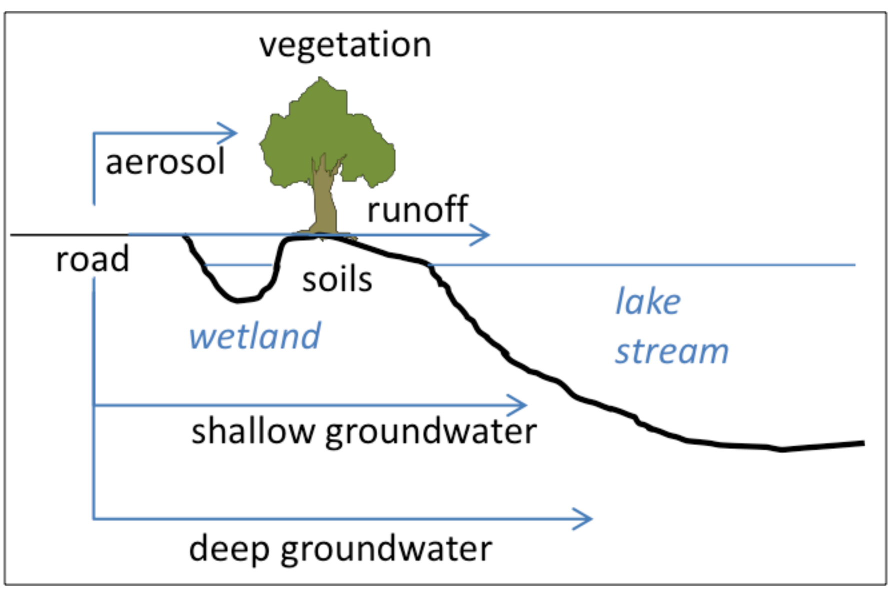


FIGURE 5.1. SALT TRANSPORT PATHWAYS IN THE ENVIRONMENT (ADAPTED FROM [53])

5.1.1 Soils

Soils contain a mixture of reactive surfaces—mainly clays, organic matter, and oxides. At relevant pH ranges, most of these surfaces have negative charges that interact with positively-charged cations, called cation exchange sites. These negatively-charged sites hold important cations for plant growth. When soils are exposed to the cations from chloride salt applications, primarily sodium, calcium, or magnesium ions, the existing soil cations can be displaced by these chloride salt cations. Both concentration of cations as well as valence electrons, charge, and size, play a role in exchange of ions. Although calcium and magnesium are more strongly held to cation exchange sites, in applications high in rock salt where sodium is the dominant cation, sodium can become the dominate exchange ions, effectively stripping the soil of several macronutrient (calcium, magnesium, potassium and ammonium) or micronutrient (copper, zinc, or manganese) cations that are required for plant growth. Researchers have also found that chloride salt applications lead to leaching of trace metals (e.g., cadmium, copper, lead, zinc, nickel) that could be toxic to organisms living in water.[54][55] The chemical mechanisms that promote leaching are different depending on the metal and could be a combination of cation exchange, enhanced solubility of metal chloride complexes, or sorption to colloidal organic matter and colloidal dispersion.[54][56] Impacts on soils have been observed as far as 100 feet from the road.[57][51]

Additional impacts have been noted on carbon and nitrogen cycling in soils, though the implications are less certain. Green and colleagues [58] observed that road salt applications alter the relative proportion of nitrate- and ammonia-based sources of nitrogen to soils. The causes could be related to changes in soil pH and subsequent changes in microbial processing rates of the different nitrogen forms. The higher rates of ammonium nitrification (the transformation of ammonia to nitrate) in salt-impacted soils could lead to increased levels of nitrate leaching to waterways. Wang et al. [59] observed higher leaching of NH_4+ and chemical oxygen demand (COD – a surrogate for organic matter content in leachate water) in soils exposed to a variety of deicer solutions, including chloride salts, nitrate salts or glycerin. Fewer leaching impacts were observed with nitrate salts or glycerin, but use of those compounds would result in other issues related to nitrogen loads in the environment from nitrate salts, or the potential for dissolved oxygen reduction in surface waters due to biochemical oxygen demand loads from glycerin.

5.1.2 Groundwater

The concerns related to chloride salt applications impacting groundwater are related to human health and aesthetics. In this case, sodium is the primary concern, with the potential to lead to hypertension.[51] EPA had also listed sodium on its 1998 contaminant candidate list for regulation with a guidance level of 20 mg/L, but has since removed it in subsequent lists from 2005 and forward (http://www2.epa.gov/ccl). In 2003, EPA advised drinking water treatment to achieve sodium levels between 30 and 60 mg/L based on taste. This level was not enforceable and was only offered as guidance. This level was set based on the presumption that drinking water is a minimal source of sodium intake for the average person (assuming consumption of 2 L water per day). The present guidance level from EPA is a maximum of 20 mg/L sodium, developed for the portion of the population on a sodium- restricted diet. The Connecticut Department of Public Health (DPH) has set 28 mg/L as the notification level for sodium in public drinking water. Recently, DPH recommended that private well owners notify their doctor if they are on salt-restricted diets and if sodium levels in their well water is over 100 mg/L.[60]

Increases in groundwater chloride levels have been strongly linked to areas of increased chloride salt use since the 1970s.[51] Concentrations of chloride in groundwater sources have been observed well above the EPA maximum concentration for drinking water of 250 mg/L. Testing of private wells is recommended annually or if the water has a salty or brackish taste. Road salt runoff or nearby road salt storage are two listed possible causes of low water quality related to chloride by DPH.[61] Ultimately, shallow groundwater sources, which typically have higher chloride concentrations, provide base flow in streams, while deeper groundwater sources can store chloride for longer time periods.

5.1.3 Surface waters

Typical chloride concentrations in surface waters range from 0 to 25 mg/L.[62] Concentrations of chloride in runoff from chloride salt application areas can approach seawater level concentrations of around 20,000 mg/L.[51] Once runoff enters streams, concentrations are diluted substantially. However, that suggests that small streams adjacent to urban areas are the most at risk for increased chloride concentrations. The heavily urbanized Toronto and Baltimore areas have observed peak chloride concentrations of up to 5,000 mg/L and prolonged concentrations in the hundreds of mg/L.[63][64]

5.1.4 Biology

Chloride salts impact biology through injury or toxicity. The main mechanism of harm is through dehydration due to osmotic stress.[23] Roadside vegetation exposed to chloride salts can uptake excess salts through the soil media or accumulate salt on foliage due to spray. Salt injuries manifest themselves in scorched leaves, later summer coloration, early defoliation, reduced growth, and necrosis. Several studies suggest that the most affected roadside vegetation is within 22 feet on uphill roadside slopes and 53 feet on downhill roadside slopes.[65][66] A further impact of increased salinity in roadside vegetated areas is the establishment of salt-tolerant and non-native species such as narrow leaved cattails (Typha angusifolia), giant reed grass (Phragmites australis), common ragweed (Ambrosia artemisiifolia), and wild carrot (Daucus carota) among others.[51] Further details on salt-tolerant and intolerant vegetation can be found in several reports on road salt use.[51][23][67]

Aquatic life is strongly impacted as well through two primary mechanisms: water circulation and osmotic regulation. Lake water circulation, and therefore oxygen and nutrient circulation, is driven in part by the density of water, which changes as salinity increases. However, few instances of a negative impact of water density changes have been observed in the literature.[23] Changes in an organism's ability to control osmotic regulation can result in toxicity. Lethal toxicity is a function of exposure, including both concentration and duration. EPA has set acute and chronic toxicity levels for chloride of 860 mg/L and 230 mg/L with durations of one hour and four days, respectively.[52] Acute toxicity is typically measured as related to a lethal dose at which 50% mortality occurs (LD50). LD50 chloride concentrations for various aquatic species were as high as 30,000 mg/L for brook trout exposed for 0.25 hours to as low as 1,853 mg/L chloride for Daphnia magna (i.e., water fleas) exposed for four days.[68] Research on the effects on benthic macroinvertebrates—small animals that live in water bodies—is mixed in terms of changes in species abundance and diversity. Some researchers report observing significant decreases in species diversity downstream of road salt application areas, while others have not observed any effects.[51] However, field research studies such as these are difficult to control and causation is difficult to pinpoint, meaning road salt may or may not have been the cause of impairment.

Amphibians are the last major class of organisms commonly examined in relation to chloride salt application due to their life cycle in wetland areas adjacent to roadways and their highly permeable skin that is sensitive to salinity changes. Increasing levels of salinity have resulted in negative effects on growth rates and survivorship of amphibians such as the green frog, wood frog, or spotted salamander.[69][70][51] As previously discussed, smaller wetlands with longer hydraulic residence times are more susceptible to chloride impacts.

Myriad secondary impacts have been observed in laboratory and field studies. Kaspari et al. [71] noted that ant communities changed their sodium chloride intake depending on how far from the road their community was established. Increasing levels of chloride in an impacted lake were correlated to a reduction in the microcrustacean populations in the lake.[72] Several tree species have been noted for their salt tolerances as well and were identified for roadside planting.[73][74][23]

5.2 ENVIRONMENTAL IMPACTS OF ALTERNATIVE DEICERS

Acetate, formate or other organic-based deicing products, as well as corrosion inhibitors, have potential environmental impacts related to dissolved oxygen levels in receiving soils or waters (Table 5.1). While many corrosion inhibitors are organic, the exact chemical makeup of these proprietary products is often unknown. Whether an organic deicing material or a corrosion inhibitor, these simple organic molecules can be readily consumed by bacteria, utilizing oxygen in the process and resulting in lower dissolved oxygen in the environment. The secondary effect of reduced oxygen in surface waters in particular is death of aquatic organisms. There are no documented instances of low dissolved oxygen levels linked to organic deicing products or corrosion inhibitors; however, they are not in widespread use.

TABLE 5.1. GENERALIZED POTENTIAL ENVIRONMENTAL IMPAIRMENT FROM SNOW AND ICE CONTROL MATERIALS (ADAPTED FROM [53])

Environmental Impact	Road Salt (NaCl)	Calcium Chloride ($CaCl_2$)	Magnesium Chloride ($MgCl_2$)	Acetates (CMA and KA)	Organic Biomass Products	Abrasives
Water Quality/Aquatic Life	Moderate: excessive chloride loading, metal contaminants	Moderate: excessive chloride loading, metal contaminants	Moderate: excessive chloride loading, metal contaminants	High: organic content leading to oxygen demand	High: organic content leading to oxygen demand, nutrient enrichment by phosphorus or nitrogen, heavy metals	High: turbidity, increased sedimentation
Air Quality	Low: leads to reduced abrasives use	Low: leads to reduced abrasives use	Low: leads to reduced abrasives use	Low: leads to reduced abrasives use	Low: leads to reduced abrasives use	High: fine particulate degrades air quality
Soils	Moderate/High: sodium accumulation breaks down soil structure and decreases permeability and soil stability, metal mobilization	Low/Moderate: improves soil structure, increases permeability, metal mobilization	Low/Moderate: improves soil structure, increases permeability, metal mobilization	Low/Moderate: improves soil structure, increases permeability, metal mobilization	Low: probably little or no effect, limited information available	Low: probably little or no effect
Vegetation	High: spray causes foliage damage, osmotic stress harms roots, chloride toxicosis	High: spray causes foliage damage, osmotic stress harms roots, chloride toxicosis	High: spray causes foliage damage, osmotic stress harms roots, chloride toxicosis	Low: little or no adverse effect, osmotic stress at high levels	Low: probably little or no effect	Low: probably little or no effect; depends on extent of transport onto roadside vegetation
Animals	Low: sodium linked to salt toxicosis and vehicle kills, magnitude unclear	Low: probably little or no effect	Low: probably little or no effect	Low: probably little or no effect	Low: probably little or no effect, limited toxicity information available	Low: probably little or no effect

5.3 SPECIFIC IMPACTS IN CONNECTICUT

5.3.1 Groundwater

The US Geological Survey (USGS) assessed chloride levels in groundwater and surface water across the northern United States based on the National Water Quality Assessment Program data from 1991-2004.[75] Groundwater well samples indicated that about 2.5% of shallow monitoring wells and 1.7% of drinking water wells had chloride concentrations above the EPA secondary maximum contaminant level of 250 mg/L (non-enforceable; for taste, odor, or corrosion concerns). Chloride concentrations for wells in urban areas were higher relative to those in agricultural or forested areas. Ratios of chloride:bromide in samples as a conservative tracer of chloride sources suggest multiple inputs including deicing salts, sewage, animal waste, potassium chloride fertilizer, brines, seawater and landfill leachate, with deicing salts as a dominant source. Historical groundwater chloride data in Connecticut from the past 100 years was compiled by Cassanelli and Robbins.[76] Since the early 1900s, average statewide chloride concentrations in well waters have increased by tenfold, and this increase has been spatially correlated with major roadways. Additional chloride concentration data in wells are expected to reside in the individual towns where the public health official makes the decision on acceptable water quality and whether to report data to the state. Currently, this data is not routinely reported to DPH.

Within the state of Connecticut, private drinking water wells have had instances of high concentrations of sodium or chloride in their wells. Since 2014, 10 cases have been reported to the private well program at DPH [77], primarily in regards to elevated chloride concentrations. Based on additional discussion with Bill Warzecha, a supervising environmental analyst in the groundwater remediation group at DEEP [78], 10 cases have been reported this season (some may overlap with DPH reported cases). The most common cause of increased sodium or chloride concentrations was stockpiling of chloride salt-laden snow on top of a well casing or shallow drinking water well. Cracks in the casing could lead to infiltration of sodium- or chloride-laden water directly into well water. In the case of shallow wells, recharge water is more rapidly mixed with well water. DEEP has a mandate to investigate the cause of contamination under the Connecticut Potable Water Law, Statute 22a-471, and the responsible parties are required to provide a resolution. The two main causes of high sodium or chloride in wells are chloride salt applications or backwash from ion exchange systems that use sodium chloride as the exchange salt. In cases with chloride salt applications to roads as the cause, some have been related to CTDOT maintained roads and some have been related to town roads. In one case, piling of snow on the corner of a property adjacent to a CTDOT and town road resulted in chloride contamination of a drinking water well. Both CTDOT and the town agreed to provide the property owner with a new well further away from the road. In other cases, resolutions such as these are more difficult due to depth of groundwater, size of the property, or setback requirements from other infrastructure. Treatment of sodium or chloride in drinking water is difficult and usually requires a reverse osmosis system, which is laborious and costly to maintain in a private residence. Alternative solutions are often drilling of a new well or various physical changes, i.e., changing where snow is stockpiled or altering water flow paths on site.

Corrosion-related repairs on well casings have also been anecdotally reported by the Connecticut Well Water Association and some screens on public drinking wells have started to corrode.[79] However, it is difficult to ascertain the main cause of the corrosion, which could be

related to expected service life or accelerated corrosion due to salinity increases.
Public drinking water quality data is recorded in a GIS database at DPH, with chloride levels reported from 2002 to present.

- A database query for samples reporting at least 75% of the regulated maximum contaminant level (MCL) resulted in 837 hits. A total of 581 of those exceed the chloride MCL of 250 mg/L. Of those samples, there are 106 unique locations, and 22 of those sources are now inactive. All but one of the sites are groundwater sources.
- A database query for samples reporting at least 75% of the notification level for sodium resulted in 2,612 hits. Of those samples, 1,700 exceed the notification level of 28 mg/L and all but 365 of those samples represent groundwater sources.

5.3.2 Surface Water

Typical sodium concentrations in surface waters are less than 20 mg/L and a survey of several reservoir systems across the state indicates that sodium levels in raw intake water are typically below this level. A few reservoirs have observed levels periodically exceeding 28 mg/L, including Mianus Reservoir in Stamford serviced by Aquarion Water Company and Lake Whitney in Hamden.[79] This was not an exhaustive survey of all surface water reservoirs, and the available data only represents quarterly sampling. With so few samples, no seasonal or inter-annual trends could be observed.

The regulations of Connecticut State Agencies, Sec. 19-13-B32(h), states that "Where sodium occurs in excess of 15 mg/l in a public drinking water supply, no sodium chlorine [chloride] shall be used for maintenance of roads, driveways, or parking areas draining to that water supply except under application rates approved by the commissioner of health, designed to prevent the sodium content of the public drinking water from exceeding 20 mg/l." In the early 1990's, CTDOT changed the deicing material applied to a special mixture of calcium chloride and sodium chloride in response to DPH concerns about elevated levels of sodium in certain drinking water watersheds; but with new best practices enacted over the past several decades, e.g. calibration of spreaders, pre-wetting and better control of application rates, the water supply concerns were addressed.

Surface water chloride measurements collected from 1991-2004 across the northern United States exceeded the chronic criterion concentration of 230 mg/L in 15 out of 100 basins sampled during the winter.[75] The density of major roads, evapotranspiration potential, and percentage of runoff were all correlated with high chloride concentrations. Chloride loads calculated across a range of surface water monitoring stations indicated urban areas had the highest chloride loads, with a median of 88 tons/sq. mi, and this was correlated with the number of wastewater discharges, evapotranspiration potential, and urban land area. Upward trends in chloride concentrations have been observed from 1990 to 2011, with inter-annual increases in streams across 13 out of 19 seasons, or 16 out of 19 winters.[80] Increasing chloride concentrations in non-deicing periods suggest storage of chloride in shallow groundwater, releasing to baseflow later in the year.

Preliminary results from a study conducted by the USGS in southeastern Connecticut have been reported.[81] Four streams—Four Mile River, Oil Mill Brook, Stony Brook, and Jordan Brook—were selected for monitoring of upstream and downstream chloride concentrations and conductance. During winter storms and following deicing activities or melt periods, stream water chloride concentrations peaked at 160 mg/L. While 160 mg/L is below the chronic toxicity criterion, levels could increase depending on road salt loads and frequency of applications. During spring and summer, conductance generally decreased, but some locations showed peaks in chloride concentrations corresponding to peaks in flow, suggesting rain events flushed chloride from soils and groundwater.

In August 2014, elevated conductivity levels of 876 µS/cm were observed by DEEP in Lyman Brook in Marlborough, relative to levels of 330 and 391 µS/cm in 2012 and 2013, respectively.[82] A detention pond near the Route 2 and Route 66 intersection contained water with conductivity levels of 2268 µS/cm. A water sample collected at this same location on December 8, 2014 had a conductivity level of 1460 µS/cm and a measured chloride concentration of 393 mg/L, which are above the water quality standards. The specific source of this conductivity increase is currently unknown. The USGS, is currently assisting DEEP in determining the source of contamination.

A study conducted by the USGS in Vermont investigated the impact of Vermont Agency of Transportation deicing practices on stream water chloride concentrations and conductivity. [83] Three main streams were chosen for analysis based on differences in land uses, road types, road densities and geometric patterns of roadway drainage. During monitoring, stream concentrations of chloride upstream of the drainage areas ranged from 8.2 to 72 mg/L, while downstream levels ranged from 7.9 to 80 mg/L, representing a very minor difference in chloride levels in the streams and well below regulatory toxicity criterion levels. One additional small tributary that flowed through a wetlands area was monitored over a full year; the mean chloride concentration was 449 mg/L, above the chronic toxicity criterion of 230 mg/L.

5.4 REGULATORY ACTIONS RELATED TO DE-ICING CHEMICALS IN NEARBY STATES

5.4.1 Total Maximum Daily Load Program

Chloride- or salinity-related impaired waters are listed under the requirements of Section 303(d) of the federal Clean Water Act. A total of 370 streams are listed as impaired for chloride, 62 for salinity, 46 for salts, 43 for chlorides, and 2 for sulfate+chloride. Of the 370 listed for chloride, 6 locations are in Massachusetts, 36 in New Hampshire, and 2 in Rhode Island. Since these are listed waters in need of regulatory action and development of total maximum daily loads (TMDLs), the specific causes are unknown. However, many list deicing materials or dense urban development as potential causes of impairment. Burrs Brook is listed as impaired for sodium in Connecticut related to surface mining activity.

In response to the need to develop TMDLs for several water bodies, the New Hampshire Department of Environmental Services convened a salt reduction workgroup with the New Hampshire Department of Transportation.

5.4.2 Environmental Management Strategies

Removal or treatment of chloride from water is difficult, costly and impractical for large volumes; thus, the only effective management strategies include reducing chloride salt application to all surfaces (including roadways, parking lots, driveways and sidewalks), altering the concentration through dilution with other waters, or re-routing runoff to less sensitive receiving waters. Management strategies that involve re-routing or dilution through the infiltration to groundwater should consider the potential residence time of this water and future concern about surface waters from the chlorides building up in the groundwater. Since chloride is a highly soluble anion, the total mass (or load) of chloride contributed to receiving waters from deicing practices will not change. Traditional stormwater best management practices will only serve to delay peak flow and reduce chloride concentrations in surface water.

5.5 CONCLUSIONS

Several environmental observations noted throughout Connecticut and the snowbelt states have raised awareness of possible environmental impacts from the use of anti-icing and deicing materials for winter highway maintenance. Groundwater concentrations of chloride have increased over the last several decades, with average concentrations in Connecticut increasing by tenfold over the past century. About 1.7-2.5% of groundwater wells across the northern United States have chloride concentrations above the secondary MCL level and more are reported each year. In at least 1,700 water samples reported in Connecticut since 2002, sodium levels in public drinking water wells or reservoirs exceeded the guidance level of 28 mg/L; however, the exact number of unique water sources is unknown. While chloride is only part of a secondary drinking water standard, meaning it does not pose a risk to human health, and sodium levels are only offered as guidance for people with low-salt diets, the instances of elevated concentrations nonetheless are a concern to the public. In the long term, concerns arise about the health of the environment as a result of chronic or acute exposure of organisms to chlorides in surface water bodies. Currently in Connecticut, there are no impaired water bodies listed for chloride and previous studies by USGS and DEEP on water bodies expected to receive high chloride concentrations and loads have not shown chloride levels to exceed the acute or chronic toxicity criterion. However, it is impossible to monitor all water bodies each year, particularly during the winter deicing periods. In 2014, a small stream in Marlborough, Connecticut, was observed with elevated chloride concentrations and the cause is currently under investigation. Further, targeted monitoring and long-term trend data should be collected to guard against future environmental issues.

The use of deicing materials for road maintenance has a variety of environmental impacts, some of which are more manageable than others. Some impacts are short term or seasonal, such as those on soils, shallow groundwater or streams, due to the flushing of deicing materials from those environments over time, while some are longer term, such as the increasing levels of chloride observed in groundwater over the past several decades. Impacts on roadside soils or vegetation are nearly impossible to mitigate with the exception of planting salt-tolerant species. Impacts on water bodies are manageable through reduced or alternative deicing material applications, re-routing of surface water runoff, or dilution. Since both sodium and chloride are difficult to remove in water treatment systems, limiting application rates and preventing high concentrations through established best management practices should be the goal.

6.0 EFFECTS OF DEICER CORROSION ON INFRASTRUCTURE AND VEHICLES

Concerns about corrosion of infrastructure and vehicles (commercial trucks and CTDOT winter maintenance equipment in particular) is the principal reason that the Connecticut General Assembly requested CTDOT to conduct a study of the corrosive effects of chemical road treatments. This section of the report provides an overview of corrosion, laboratory studies of the corrosive effects of chlorides and acetates on concrete, steel and asphalt, and the effects of corrosion regionally and within Connecticut for roadways and bridges, motor vehicles, winter maintenance equipment, and other structures and appurtenances adjacent to roadways. Methods to address corrosion and minimize its effects are presented from the literature reviewed and presentations made to the CASE Study Committee.

6.1 OVERVIEW OF CORROSION

***Corrosion**: The deterioration of a material or its properties because of a reaction of that material with its chemical environment. Traditionally thought of only as deterioration of metal (e.g., rusting of steel), but now expanded to include degradation of non-metallic materials as well. Some nontraditional examples include rotting of wood, degradation of concrete (carbonation, alkali-silica reaction phenomena), and degradation of composite materials due to reaction with the environment.*[84]

A report commissioned by the FHWA in 1999 on the cost of corrosion and prevention strategies in the United States estimated the annual cost of corrosion on steel highway bridge components to be $2 billion for maintenance and the cost of capital improvements for bridge substructures and superstructures, and approximately $500 million for the maintenance painting cost for steel bridges (Figure 6.1). The estimated total annual cost for highway bridges due to corrosion is $8.3 billion. This is 3% of the estimated annual overall cost of corrosion to the US economy ($276 billion).[40][85]

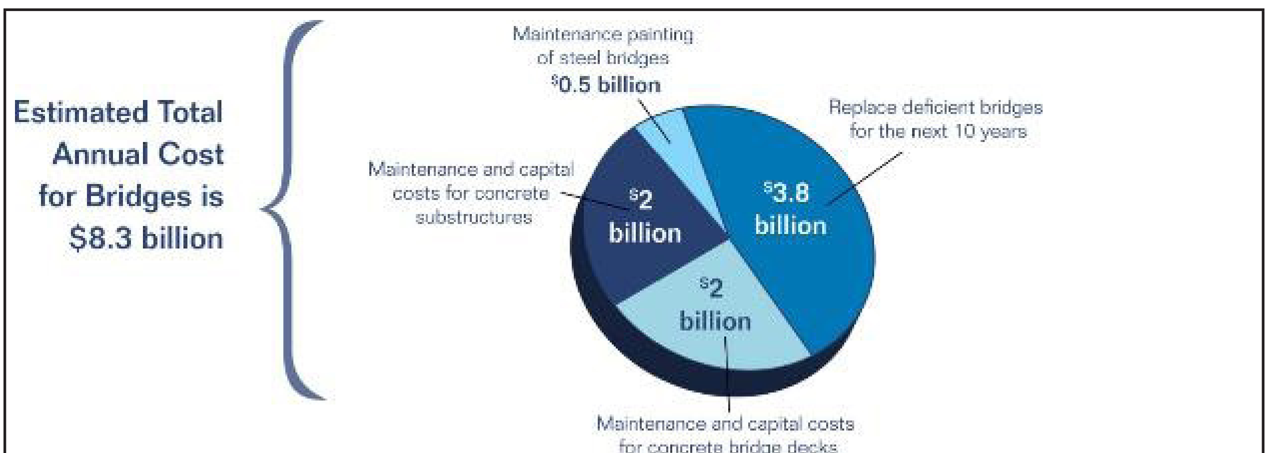


FIGURE 6.1. ESTIMATED ANNUAL COST IN DOLLARS (1999) IN THE UNITED STATES DUE TO CORROSION OF BRIDGES (SOURCE: REFERENCE [85])

This study also summarized the annual corrosion-related costs to motor vehicles to be approximately $23.4 billion per year. This cost was divided into three components: (1) increased manufacturing cost because of corrosion engineering and the use of corrosion-resistant materials ($2.56 billion per year); (2) repairs and maintenance necessitated by corrosion ($6.45 billion per year); and (3) corrosion-related depreciation of vehicles ($14.46 billion per year).[85]

Additionally, to keep highways free of snow and ice and to maintain a reasonable level of service during winter weather, it is estimated that each year approximately $2.3 billion is being spent for highway winter maintenance in the United States.[86]

An interesting fact is that regardless of the commonly voiced concern that motor vehicles are more subject to corrosion due to an increase in the use of chlorides, statistics about automotive ownership from multiple sources show that the average age of vehicles in operation has increased continuously since 1969.[87] The average age for passenger cars in 1969 was reported to be 5.1 years[87]; in 1995 it was 8.4 years; and in 2013, 11.4 years.[88] This may be the result of many factors, including increased reliability, higher vehicle prices, economic changes, and owner satisfaction/comfort levels. Improvements in design that delay the onset of corrosion may also be a factor in increased longevity of ownership.

Joseph Payer, Chief Scientist of the National Corrosion Center, University of Akron, noted in a presentation to the CASE Study Committee on October 20, 2014, that corrosion preventive strategies for highway infrastructure and vehicles are needed. These strategies are both non-technical (increased awareness, elimination of a misconception that nothing can be done, a need for changed policies, regulations, standards and management practices, and improved education and training) and technical (implementation of advanced design practices, a need to advance life prediction and performance assessment methods, as well as research development and the implementation of corrosion technologies).[89]

It is assumed that deicing salts are a major contributing factor to corrosion of both infrastructure and vehicles, although other factors can contribute to significant corrosion of vehicles and infrastructure. Some of these factors include proximity to the ocean as well as the normal relative levels of humidity, as corrosion cannot occur without the availability of moisture. Even without exposure to deicing chemicals, corrosion would eventually occur by natural processes. Figure 6.2 delineates areas that are prone to corrosion in the eastern United States.

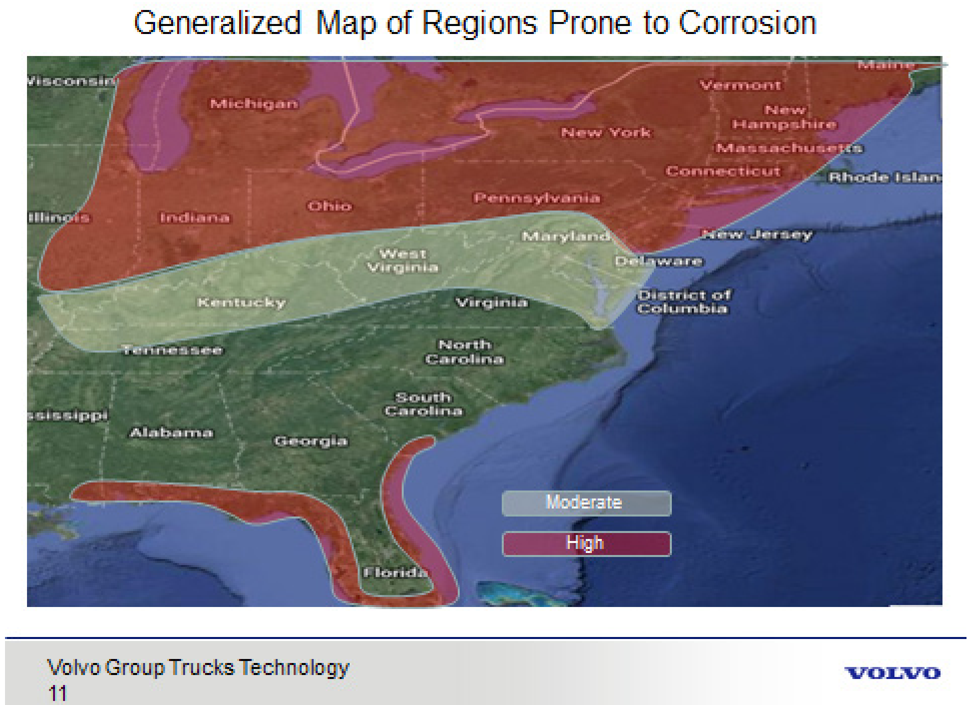


FIGURE 6.2. AREAS OF EASTERN UNITED STATES PRONE TO CORROSION
(COURTESY OF VOLVO TRUCK GROUPS TECHNOLOGY [90])

As previously noted in this report, there are three chloride-based deicing chemicals that are commonly used: sodium chloride, calcium chloride and magnesium chloride. However, identifying which of these chloride-based chemicals is the most damaging is neither a simple nor a straightforward process. The corrosion of reinforcing steel used in concrete structures is a very good example of the complexity associated with identifying if one chloride-based deicing chemical is less damaging than the others. Corrosion of this type of steel has been linked to each of the three noted deicing chemicals. Standard laboratory tests for corrosion exist; however, some of them are less rigorous than desired. As a result, as stated in NCHRP 577, "*There have been claims regarding the relative corrosion of these products; however, there is some disagreement in the literature*".[40]

Sodium chloride has been used for more than 50 years and its associated long-term effects on reinforced concrete are fairly well understood. Although there has been extensive research into the use of alternative materials (e.g., magnesium chloride, calcium chloride, and calcium magnesium acetate [CMA]), there is only limited data about their long-term effects.[40]

6.2 INFRASTRUCTURE

6.2.1 Laboratory Tests for the Effects of Chlorides and Acetates on Portland Cement Concrete

"*Deicers can affect concrete both physically and chemically. Physical effects are typically manifested as cracking and salt scaling, while chemical effects can result from reactions involving cement hydration products, aggregates, or reinforcing steel*".[21]

The physical effects of deicers are mainly due to damage from freeze-thaw cycling. An endothermic reaction of some deicers, such as sodium chloride, can lead to rapid cooling at the pavement surface, known as thermal shock. The "glue spall mechanism" is reported in [91] to be a deteriorating mechanism in this regard.

> *When a solution freezes on a concrete surface an ice/concrete bi-material composite forms. As the composite temperature is reduced below the melting point of the solution, the ice layer tends to contract 5 times as much as the underlying concrete.* [91]

The ice will crack under tension and the cracks propagate into the concrete's surface, eventually leading to surface deterioration such as spalling, scaling and delamination of the concrete (See Figures 6.4, 6.7 and 6.8). However, Valenza and Scherer [91] conclude that thermal shock is a negligible contributor for surface scaling damage.

The formation of salt crystals and the hygroscopic effect of winter salts also contribute to physical deterioration. Dissolved salts ingress to PCC pores and increase their volume during precipitation and crystallization. This increases pressure on hardened concrete paste and aggregate. An increase in water pressure, as much as 10%, may occur within the concrete as the water is attracted to salts.

The chemical effects of deicers include reactions that can occur with cement paste, expansive aggregate reactions, and corrosion of steel reinforcement. In PCC, calcium silicate hydrate (C-S-H) comprises about 50% of the volume of cement paste, and is considered to be a primary source of concrete strength. Calcium hydroxide represents another 20% - 25% of the volume. If calcium hydroxide is leached out through chemical reactions with magnesium chloride or CMA, the porosity of the pavement increases. This increase in porosity, along with pores that already exist from air entrainment during construction of the PCC, allow for penetration of deicing chemicals into the concrete. This chloride penetration can increase the overall susceptibility for freeze-thaw damage and lead to destruction of the passive layer around embedded steel reinforcement, which can result in accelerated steel corrosion.

Figures 6.3 through 6.8 show examples of various concrete distresses that result in the field for various reasons, including the use of chemical deicers containing chlorides.

FIGURE 6.3. PORTLAND CEMENT CONCRETE SURFACE MAP CRACKING (PHOTO FROM [92])

Surface Map Cracking *– is a series of interconnected hairline cracks in PCC pavements that extend only into the upper surface of the concrete; includes cracking typically associated with alkali-silica reactivity.* ***Alkali-Silica Reaction*** *(ASR) is the reaction between alkalis (sodium and potassium) in Portland cement and certain siliceous rocks or minerals, such as opaline chert, strained quartz, and acidic volcanic glass, present in some aggregates. The products of the reaction may cause abnormal expansion and cracking of concrete in service.[92]*

FIGURE 6.4. PORTLAND CEMENT CONCRETE SURFACE SCALING (PHOTO FROM [92])

Surface Scaling *– is local flaking or peeling away of the near surface portion (the upper 1/8 to ½ in.) of hardened concrete resulting in the loss of surface mortar.*

FIGURE 6.5. POPOUT (PHOTO FROM [93])

Popouts *- A popout is a small piece of concrete pavement that has broken away from the surface of the concrete due to localized internal pressure that leaves a shallow, typically conical, depression.*

FIGURE 6.6. MODERATE SEVERITY DURABILITY "D" CRACKING (PHOTO FROM [92])

Durability "D" Cracking *– is the breakup of concrete due to freeze-thaw expansive pressures within certain aggregates.*

FIGURE 6.7. SPALLING ALONG A LONGITUDINAL JOINT (PHOTO FROM [93])

Spalling *- cracking, breaking, chipping, or fraying of the concrete slab surface within 2 ft. of a joint or crack.*

FIGURE 6.8. DELAMINATION AND TRANSVERSE CRACK (PHOTO FROM [93])

Delamination *is a separation along a plane parallel to a surface and generally near, the upper surface. It is found most frequently in bridge decks and caused by the corrosion of reinforcing steel or freezing and thawing. Delamination is similar to spalling, scaling, or peeling except that delamination can affect large areas.[92]*

A comprehensive report titled "Physical and Chemical Effects of Deicers on Concrete Pavement: Literature Review" [21] was prepared at Brigham Young University for the Utah DOT in 2013. This report provides a review and summary of the effects of the three noted chloride deicers and CMA on concrete pavement. Ten laboratory test studies that were published between 1995 and 2012 are summarized in the Utah report. These laboratory test studies generally involve one or more of three types of tests: freeze/thaw cycling (F/T), wet-dry cycling (W/D), or soaking specimens in solutions of chemicals and water for periods of time ranging from days to years. It is noted that the laboratory test methods used vary considerably among most of these studies.

All 10 studies, with the exception of one, provided evidence that magnesium chloride and calcium chloride are more detrimental to PCC than sodium chloride. Some of the chemical reactions that cause concrete deterioration and damage include:

- leaching of calcium hydroxide from the cement paste,
- a chemical conversion of beneficial C-S-H to non-cementitious Magnesium Silicate Hydrate (M-S-H), (a powder-like substance that provides no strength to the pavement),
- formation of brucite crystals (magnesium hydroxide) from reactions with magnesium chloride that cause pressure and concrete expansion,
- formation of other complex salts that can expand and cause destructive pressure, and
- formation of oxychlorides from reactions with calcium chloride that can generate destructive hydraulic pressures, as well.

More specifically, specimens exposed during laboratory tests to calcium chloride deteriorated from formation of calcium oxychloride ($3CaO \bullet CaCl_2 \bullet 15H_2O$) and complex salts. Specimens exposed to magnesium chloride and CMA deteriorated because of M-S-H and brucite formation.

Calcium chloride deterioration yields the following: [94]

$$3Ca(OH)_2 + CaCl_2 + 12H_2O \rightarrow 3CaO \bullet CaCl_2 \bullet 15H_2O$$

Magnesium chloride deterioration occurs in the following manner: [94]

$$x\ CaO.SiO_2.l\ H_2O + x\ MgCl_2 + m\ H_2O \rightarrow y\ MgO.SiO_2.nH_2O + (x-y)Mg(OH)_2 + x\ CaCl_2.2H_2O$$

Where: l + m = n + 3x – y, and can be simply represented by:

$$CSH + MgCl_2 \rightarrow MSH + CaCl_2$$

$$Ca(OH)_2 + MgCl_2 \rightarrow Mg(OH)_2 + CaCl_2$$

Corrosion that causes expansion of the steel and imparts stress to the surrounding concrete is initiated by critical concentrations of chloride ions in the vicinity. This can lead to delamination (Figure 6.8) of the concrete. Generally, for corrosion to initiate on the embedded steel, one to two pounds of chloride ions per cubic yard of concrete are needed. The studies found that calcium chloride and magnesium chloride typically had a much greater negative effect on corrosion of embedded steel in concrete than sodium chloride.[21] Once the threshold limit of chloride concentration has been exceeded, which causes a loss of the protective layer around the steel due to a decrease in the pH-value, the corrosion reaction of the steel starts as follows:

- Anode / Half-cell oxidation:

$$Fe \rightarrow Fe^{2+} + 2\ e^- \ (\text{or: } Fe + 2Cl^- \rightarrow FeCl_2 + 2\ e^-)$$

- Cathode / Reduction reaction:

$$O_2 + 2H_2O + 4\ e^- \rightarrow 4OH^-$$

- Formation of iron hydroxide or rust:

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2$$

$$4Fe(OH)_2 + O_2 \rightarrow 4FeOOH + 2H_2O$$

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$$

$$2Fe(OH)_3 \rightarrow Fe2O_3 + 3H_2O$$

The increase in volume of the corroded steel leads to cracking and/or spalling of the concrete structure (Figure 6.7).

The threshold limit of chloride concentration is dependent on the pH value of the concrete. Carbonation, which reduces the pH value through the following equation, $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$, decreases the level of chloride concentration needed for corrosion, and therefore accelerates steel corrosion.

Alkali-silica reaction (ASR) in concrete (Figure 6.3) occurs with aggregates containing reactive silica. The gel, which can form by the reaction of silica and alkali hydroxides, has the ability to adsorb water from the surrounding paste or environment, generating an expansive pressure capable of damaging concrete and creating cracks. When calcium chloride and sodium chloride are used on concrete containing silica reactive aggregates, the ASR can be initiated and accelerated through the supply of alkalis.

Another deleterious process observed in concrete structures is the Alkali Carbonate Reaction (ACR), which could be caused by magnesium chloride and calcium chloride in the presence of reactive dolomite (calcium magnesium carbonate) and cement paste. The reaction between dolomite from the aggregates with hydroxide anions in the cement paste releases magnesium cations and carbonate anions. The magnesium cation is involved in the process of brucite formation, while carbonate reacts with portlandite to form calcite and hydroxide ions. Brucite and calcite are crystals that grow and create an internal pressure in concrete. Also, magnesium chloride is responsible for the availability of magnesium cations that are directly involved with the formation of brucite. Calcium chloride was found to accelerate ACR by improving the de-dolomitisation reactions, which releases magnesium to form more brucite and MSH.

Table 6.1 is a reproduction of a table from the Utah report [21] that shows the generalized results of the 10 laboratory studies. More specific information about these studies can be found in the Utah report or the original studies that are referenced in column 2 of Table 6-1.

TABLE 6.1. SUMMARY OF THE EFFECTS OF COMMON DEICERS ON CONCRETE (SOURCE: REFERENCE [21])

Study	Reference	Method*	Sodium Chloride	Calcium Chloride	Magnesium Chloride	CMA
Peterson 1995	[95]	Soak	Minor	-	-	Significant
Cody et al. 1996	[96]	Soak, F/T, W/D	Minor	Significant	Significant	-
Lee et al. 2000	[97]	F/T, W/D	Minor	Significant	Significant	Significant
Sutter et al. 2006	[98]	Soak	Minor	Significant	Significant	-
Wang, Nelson, and Nixon 2006	[99]	F/T, W/D	Minor	Significant	-	-
Darwin et al. 2008	[100]	W/D	Minor	Significant	Significant	Significant
Poursaee, Laurent, and Hansson 2010	[101]	W/D	Minor	Significant	Significant	-
Shi et al. 2010	[102]	F/T	Significant	-	Minor	Minor
Shi et al. 2011	[103]	Soak	Minor	Significant	Significant	-
Jain et al. 2012	[104]	F/T, W/D	Minor	Significant	Significant	-
*F/T = freeze-thaw cycles *W/D = wet-dry cycles *Soak = immersion in chemical (salt) bath						

Even though the results of lab tests summarized in Table 6.1 appear to be generally in agreement "*the results of studies on the effects of deicers on concrete can vary greatly, because they strongly depend on such factors as exposure conditions, concentrations of the deicers, and test temperature*".[104] These variables, as well as others such as sample type (e.g., lab-produced mortar or plain PCC, concrete containing reinforcement, and cores from existing pavements), mix design and materials used, sample specimen size and shape used in the testing, and test method and length of testing period varied within the studies and can affect the results. These testing variations can be discerned in more detail in Appendix G (Summary of Laboratory Study Literature for Deicer Chemicals and Portland Cement Concrete).

> *Regardless of variations in testing methods and specimen characteristics, the results from nine of the ten studies summarized in this research indicate that specimens exposed to sodium chloride experienced only minor, if any, adverse effects, while specimens exposed to calcium chloride, magnesium chloride, or CMA experienced significant deterioration, including scaling, cracking, mass loss, and compressive strength loss.*[21]

The Utah report includes the following recommendation that is based on review of laboratory studies that were performed between 1995 and 2012: *"…. engineers responsible* ***for winter maintenance of concrete pavement****s should utilize sodium chloride whenever possible, instead of calcium chloride, magnesium chloride, or CMA, and apply only the amount that is absolutely necessary to ensure the safety of the traveling public."* In addition to the traditional considerations of price, environmental effects and product functionality, the report indicates that the damaging effects of deicers should also be considered when selecting a deicer product.[21]

Also, a study conducted on behalf of the South Dakota DOT found that "*it was determined that there is significant evidence that magnesium chloride and calcium chloride chemically interact with hardened Portland cement paste in concrete resulting in expansive cracking, increased permeability, and a significant loss in compressive strength. Although the same effects were not seen with sodium chloride brines, it was shown that sodium chloride brines have the highest rate of ingress into hardened concrete. This latter fact is significant with respect to corrosion of embedded steel*".[105] This study included recommendations on how to mitigate the effects of chloride deicers on concrete as follows:

- One strategy is to use fewer chlorides for anti-icing and deicing
- Another longer-term strategy is to construct concrete pavements and bridge decks that are less susceptible to chloride-induced deterioration. It was found in South Dakota that *"a reduction in concrete or mortar permeability resulted in less damage in the same amount of exposure time for similar mixtures and exposure solutions."* The use of ground slag or fly ash in the concrete mixtures is another option.
- As a maintenance strategy, sealants could be applied to help slow the ingress of the deicing chemicals, thereby minimizing the impact these chemicals will have on concrete pavement and structures.[105]

Additional needs for research on concrete deterioration from deicers have been identified as well. A January 2014 NCHRP Research Needs Statement titled "Influence of Deicer Salts on Joint Deterioration and Durability of Concrete" [106] states:

> *… in light of the increasing demand and popularity of alternative deicers, alternate application methods, and their potential to cause durability problems in concrete, it is important that a comprehensive research study be initiated to study the impact that these deicers may have on highway infrastructure. Of concern are the influence the deicers have on scaling and freeze-thaw resistance of concrete, potential chemical reactions involving the deicers and the hydrated cement paste and/or aggregate in the concrete, and corrosion of embedded steel reinforcement. The pay-off from this research will be recommendations for selecting effective yet benign deicers and anti-icers as well as potential mixture design solutions and best construction practices. This will not only ensure safe-driving conditions but also long-term durability and service life of our transportation infrastructure assets.*[106]

Another pending 2013 NCHRP Research Needs Statement titled "Influence of Potassium Acetate Deicers on Durability of Concrete" that is available online [107] suggests that the increased use of potassium acetate at airports and on specific highway bridges with automated pre-treatment systems deserves study of potential deterioration of concrete. The problem statement notes that

> *…concerns have been expressed by the Federal Aviation Administration (FAA) on the effect of potassium acetate deicers on durability of concrete in airfield pavements. Recent investigations at selected airports have suggested that potassium acetate-based deicers may have led to premature distress in certain concrete pavements. An FAA study funded by Innovative Pavements Research Foundation (IPRF) is presently just underway. However, preliminary findings from the study indicate that the deicers have the potential to induce aggressive alkali-silica reactions in certain concretes.*[107]

The following subsection provides information about potential discrepancies between laboratory and field results with regard to potassium acetate.

6.2.2 Field Tests for the Effects of Chlorides and Acetates on Portland Cement Concrete

> *Field studies of existing highways provide crucial observations, but there are significant problems in relying solely on field observations to evaluate deicer-induced accelerated deterioration. In addition, field conditions are so varied in terms of highway use by trucks and cars, temperature variations, precipitation rates and seasonal patterns, and concrete composition including type of coarse aggregate, for example, that definitive conclusions about deicer-induced deterioration are difficult to determine.*[96]

The previous section discussed the review of the effects of chemical deicers on concrete based on laboratory studies. Some of those studies indicated that there is no direct correlation with actual field conditions. As a result, in 2011 Oregon DOT commissioned a study [108] to investigate the effects of chloride deicers on concrete bridge decks and to identify and evaluate best practices and products to mitigate such effects. The objectives of the project were to:

> *(1) determine whether the accumulated application of $MgCl_2$ and sodium chloride (NaCl) deicers have caused significant damage to the concrete typically seen in the bridge decks maintained by the Oregon DOT and other DOTs; (2) quantify the chloride ingress from winter road operations and estimate the potential for damage to reinforced concrete; (3) develop a practical, on-site measurement method to assess the exposure of concrete components to chloride deicers; (4) create a tool to estimate current and future damage states due to applying $MgCl_2$ deicer; and (5) identify, test, and recommend methods of mitigating deicer-induced damage to existing concrete infrastructure in the State of Oregon.* [108]

The results of this study were published in late 2014. The project collected, examined and tested field cores from 12 Oregon DOT bridge decks (predominantly exposed to magnesium chloride deicer), two Utah DOT bridge decks (predominantly exposed to sodium chloride deicer) and two Nebraska Department of Roads bridge decks (mainly exposed to potassium acetate deicer). The field cores were tested for mechanical properties and to detect possible chloride penetration, carbonation, and ASR, and were also subjected to petrographic analysis to characterize the cement paste and PCC air contents. The study conclusions, among others, included:

- The concrete bridge decks exposed to potassium acetate or magnesium chloride deicer showed significant reductions in splitting tensile strength and microhardness, whereas surface-distress-free decks exposed to sodium chloride deicer did not.
- Visual inspection for assessing the condition of concrete bridge decks exposed to magnesium chloride deicer would be misleading, as the chemical attack generally does not exhibit apparent signs of distress until severe disintegration of the concrete occurs.
- The role of magnesium chloride in the carbonation and ASR of field concrete, if any, is not significant, but potassium acetate may play a significant role in contributing to ASR in concrete containing reactive aggregate.
- The microscopic evidence further suggested that the concrete in the field environment had been affected by both physical and chemical damage from magnesium chloride. [108]

The following includes some of the recommendations from the report:

> *To address the potential risk of $MgCl_2$ magnesium chloride], NaCl [sodium chloride] and KAc [potassium acetate] deicers, agencies such as [Oregon DOT] should continue to implement changes in the concrete mix design and in the construction, maintenance, or rehabilitation practices for concrete decks. Surface treatments, especially penetrating sealers and water repellents should be used to protect new concrete and existing concrete without too much chloride contamination. Future work should be conducted to explore the penetrating ability and concrete-bond strength and bond longevity of surface treatments.[108]*

Although the above results appear to corroborate the lab studies cited previously, it should be emphasized that the Oregon study involved decks in three states with many possible variables that could also affect the study results, such as weather, construction techniques, materials (aggregates and cements), traffic levels, amount of deicers applied and age of bridges. Therefore, some caution should be taken about the study results by keeping these factors in mind.

A summary presentation of several research studies (University of Toronto, Michigan Technological University, University of New Brunswick and Clemson University) on "Potassium Acetate Effects on Concrete Durability" was made as a web session sponsored by the American Concrete Institute, by Paul Tennis, Portland Cement Association in January 2014.[109] Some of the conclusions were that the laboratory studies indicated that potassium acetate could be a problem by accelerating ASR deterioration. However, a comparison of field sites concluded that there was not a correlation between the laboratory studies and what was found in the field. In fact, it was shown that at the field sites, after 15-20 years of exposure to potassium acetate, the deterioration found was not attributable to potassium acetate, but rather to poor construction practices.[109]

6.2.3 *Effects of Chlorides and Acetates on Steel Reinforced Concrete*

Reinforced concrete structures, which are most highway structures other than plain concrete pavements, can potentially be negatively impacted by all types of chlorides. The salts penetrate concrete bridge components including concrete decks that are vulnerable to salt-induced damage. These components include reinforced concrete supports (e.g., beams), steel structural supports, bearings, and joint devices. Damage to these components caused by salt leaking from the deck and salt splash and spray from adjacent roadways is generally less extensive than deck damage, but is often more difficult and expensive to repair and protect against.[23]

The high alkalinity of PCC (pH > 12.5) when initially constructed protects embedded steel from corrosion. Cations like calcium, magnesium and sodium react with the hydroxyls from the concrete paste, reducing the concentration of hydroxide anions, which compounds a passive film of about 10 nanometers thick; this film is responsible for effectively insulating the steel and the electrolytes so that the corrosion rate is negligible.[110] According to NCHRP 577, [40] chloride-induced corrosion poses the greatest risk to structural integrity because it causes localized attack of the steel. Salts allow ingress of chlorides into the pore structure of the concrete. Tensile forces on concrete exert enough pressure to cause cracking, delamination and spalling of the concrete (See Figures 6.3 through 6.8). It seems intuitive that corrosion of steel reinforcement within concrete would be similar for all three chlorides. However, the application rates, and whether in liquid or solid format, can vary the potential rate of ingress to the reinforcement.

NCHRP study #577 [40] notes "*that corrosion of reinforced steel seems inevitable with chlorides, but the time to corrosion may vary by product and by condition of the PCC.*" Other factors that could affect the relative corrosion rate would be depth of steel from surface of concrete, weather conditions such as number of freeze/thaw cycles, chemical application rates, concentration of chemicals when applied, and the diffusion of chloride ions within the concrete, among others.[40]

The measurement of chloride ion concentration in concrete has been widely used to predict the corrosion level of embedded steel. However, other deicing chemicals such as acetates (potassium acetate, sodium acetate), urea and propylene glycol do not have common indicators such as chlorides for field measurement.

In general, the resistance of concrete to chloride penetration is affected by construction techniques (finishing, curing, and workmanship), environment (traffic loading and weather), mixture composition, and age. According to Shi et al [111]

> *There are many ways to manage the corrosive effects of deicers, such as: selection of high-quality concrete, adequate concrete cover and alternative reinforcement, control of the ingress and accumulation of deleterious species, injection of beneficial species into concrete, and use of non-corrosive deicer alternatives and optimal application rates*.

Theoretically, a high quality concrete mix (water/cement ratio of 0.40) will result in lower diffusion of all chlorides. On the other hand, as previously indicated, magnesium chloride can open up the pore structure in concrete when reactions with calcium hydroxide occur, thus allowing for more chloride intake and diffusion. NCHRP report 577 [40] notes that while 50 years of information exists about the use and effects of sodium chloride, magnesium chloride has been used as a deicer for a relatively short period of time, which makes predictions of long-term effects on concrete and steel reinforcement difficult.

6.2.4 *Summary of the Effects of Chlorides on Portland Cement Concrete and Reinforced Concrete*

In summary the following deteriorating mechanisms of concrete due to winter salts are

- leaching of calcium hydroxide
- decalcifying of C-S-H
- converting of C-S-H to M-S-H
- forming of brucite, complex salts and oxychlorides
- lowering of the pH (accelerates carbonation)
- increasing pore size and pore volume, leading to increased permeability and thus increased susceptibility to environmental aggressors, such as chlorides
- initiating and accelerating alkali-silica reaction and alkali-carbonate reaction

6.2.5 *Effects of Deicers on Asphalt Pavements*

There is very little (if any) chemical interaction between chloride-based deicers and asphalt pavements. Therefore, it can be concluded that chloride-based deicers do not damage asphalt pavements directly. Stating the effect of organic deicers such as potassium acetate or agricultural byproducts on asphalt pavements is more speculative, since they are for the most part not used in Connecticut, but given the nature of asphalt, it is unlikely that these materials would negatively impact Connecticut's asphalt pavements.

Asphalt pavements undergo aging and deterioration due to exposure to weather, oxidation, temperature variations, moisture intrusion, and resultant cyclic expansion and contraction. This type of pavement also undergoes differential vertical movement due to frost heaves that can occur under the surface layers where frost-susceptible soils exist. These processes contribute to the eventual deterioration of the asphalt, resulting in thermal cracks, water intrusion, increased oxidation, and physical failures, such as potholes and raveling.

The use of deicing chemicals can induce additional freeze-thaw cycles in both asphalt and concrete. This is caused by the temporary melting of snow and ice from the application of deicers during a period of sustained freezing temperatures. The liquid water can then seep into materials until either the salt concentration drops to allow the refreezing of the water or the ambient temperature drops below the altered freeze point of the water/deicing chemical solution. Another way that deicers, particularly sodium chloride, can increase the number of freeze-thaw cycles has to do with the endothermic reaction that takes places when solid sodium chloride is dissolved in water. This endothermic reaction will reduce the temperature of the surrounding materials and can temporarily cause the water-deicer combination to freeze [27].

6.2.6 *Corrosion of Steel Bridges, Roadside Appurtenances and Utilities*

Bridge structures are typically the most extensive steel infrastructure maintained by DOTs. Federal law (National Bridge Inspection Standards 23 CFR 650 Subpart C) [112] requires that roadway bridges 20 feet or longer in length be inspected at least once every two years. Federal guidelines classify roadway bridges as structurally deficient if one or more of the three key components (deck, superstructure, or substructure) or a culvert or retaining wall is rated four or less for condition (on a 0-9 scale) or receives an appraisal rating of two or less for structural condition or waterway adequacy.[114] The definitions of deck, superstructure or substructure are pictorially shown in Figure 6.9).

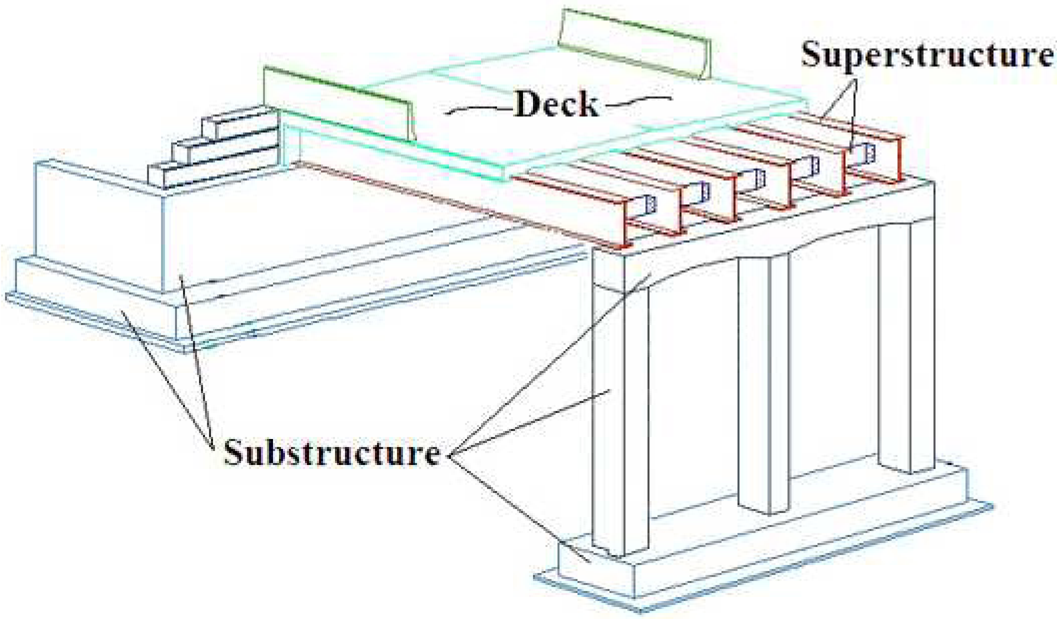


FIGURE 6.9. BRIDGE ELEMENTS DIAGRAM (SOURCE: MICHIGAN DOT [115])

A structurally deficient bridge is not necessarily unsafe to cross. In addition to those bridges that are rated "poor" (4 or less), CTDOT also classifies bridges with very low load ratings (less than 12 tons capacity) which require replacement, and bridges with an insufficient waterway opening, causing frequent flooding resulting in severe traffic delays, as structurally deficient. A restriction of use by heavy vehicles on structurally deficient bridges may be imposed until repairs are made.[116]

During 2014 (latest available data released by CTDOT in May 2015) CTDOT inspected 3,998 bridges on CTDOT-maintained roadways. 292 (7.3%) of these structures were rated as structurally deficient.[117] Almost 1,300 additional bridges owned by Connecticut's municipalities, DEEP, or located on private property are inspected by, but not maintained by, CTDOT.

Table 6.3 shows Connecticut's bridge conditions in December 2014 (2013 data) relative to surrounding states during 2013, as compiled by FHWA. For this table, it must be noted that the total bridges listed for Connecticut (4218), which doesn't match the total cited above for 2014, includes approximately 220 additional bridges inspected by CTDOT, but not located on their maintained roadways. It is shown in Table 6.3 that relative to surrounding states, Connecticut's deficient bridges are less numerous, on a percentage basis, than two-thirds of the states presented.[118]

TABLE 6.3. CONDITION OF ROADWAY BRIDGES IN THE NEW ENGLAND STATES, NEW YORK AND NEW JERSEY

State	**Total # of Bridges (December 2014) (1)**	**Total # of Structurally Deficient Bridges (December 2014) (1)**	**% *of Total* Bridges that are Structurally Deficient (December 2014)**
New York	17,456	2,012	11.5%
New Jersey	6,609	621	9.4%
Massachusetts	5,141	459	8.9%
Connecticut (2)	**4,218**	**378**	**9.0%**
Vermont	2,745	206	7.5%
New Hampshire	2,467	324	13.1%
Maine	2,419	364	15.1%
Rhode Island	766	174	22.7%
Totals	***41,821***	***4,538***	***10.9%***

(1) Source: Reference [118]; Includes bridges maintained by state DOTs
(2) includes approximately 220 additional bridges inspected by CTDOT, but not located on their maintained roadways

The American Society of Civil Engineering (ASCE) 2013 Report Card for America's Infrastructure [119] reports that *"… one in nine of the nation's bridges are rated as structurally deficient, while the average age of the nation's 607,380 bridges is currently 42 years."* Further it is noted that 30% of the existing bridges have already exceeded their design life. It is estimated that $76 billion would be needed to repair only deficient bridges. It is estimated that $121 billion would need to be invested to bring the condition of the nation's bridges to a level that meets the current traffic demands. Thus an annual investment of $20.5 billion is needed to make the nation's bridges capable of meeting the traffic demand by 2028.[119] Corrosion of steel members and degradation of concrete elements are the main source of infrastructure deterioration.

It is virtually impossible to identify the precise extent of corrosion that is caused by winter deicing chemicals alone on bridges in Connecticut. It is intuitive that states located in northern climates such as Connecticut that rely heavily on the use of chlorides for winter highway maintenance have the greatest risk for damage to highway infrastructure. This impact is likely second only to maritime locations where exposure to salt water and salt spray are frequent. The Connecticut shoreline has both maritime and winter chemical exposure.

The mechanism for deterioration of steel is similar to that presented on reinforced concrete, and is, therefore, not repeated. The more hygroscopic nature of magnesium chloride and calcium chloride compared to sodium chloride indicates that exposure to these chemicals without removal from rain or rinsing might lead to greater levels of corrosion at an earlier life-cycle stage.

There are specific areas of bridges, such as directly below joints, the ends of beams and structural members, rocker bearing pads and drainage conduits that are most susceptible to trapping moisture and debris. These are areas that require close watching and hold promise for greatest benefit from cleaning and retrofitting with corrosion resistant materials (see Section 6.5 for further discussion.)

Other significant roadside infrastructure that has the potential to be negatively affected by corrosion includes drainage structures, controller boxes, sign posts, overhead sign structures and supports including variable message signs, traffic signal lights, lamp posts and street lights, video cameras, guiderails, fencing, and bridge rails. Rehabilitation of overhead sign structures to correct corrosion and wind load failure susceptibility has been an ongoing CTDOT effort for several years.

In addition, structures adjacent to roadways that are not owned by the state or a municipality that is responsible for the roadway could be susceptible to corrosion. Of particular interest, due to extent and value, would be above- and underground utilities (i.e., sewers, gas lines, water mains, telephone lines, communication cables, and electrical lines) that are close to or within the roadway right-of-way. In addition, adjacent storage tanks, advertising signs, monuments and statues have a potential to be affected by corrosion.

In an effort to identify the existence and extent of corrosion, if any, to utility infrastructure, United Illuminating and Eversource were contacted. Both companies, each with considerable infrastructure within Connecticut, indicated that corrosion was under control. Their cabling has cathodic protection and underground vaults are either stainless steel or if regular steel is used, sacrificial anodes attached to them. Stainless steel skirts for transformers and control boxes and non-steel racks are also used for underground vaults. The company representatives indicated that corrosion due to use of winter road treatments was not a major concern at this time.

6.3 MOTOR VEHICLES AND TRUCKS

A February 2015 CBS News report indicated that US motorists spend as much as $6.5 billion per year on vehicle repairs that are caused by corrosion from winter highway maintenance.[120] Also, there is documented evidence that corrosion of motor vehicles has been a concern for at least 75 years. In a report published in 1949]121] it was observed and reported in Michigan that

> *In recent years the increased use of sodium chloride (rock salt) and calcium chloride on highways for ice control and dust palliation has drawn considerable comment from motorists, a great majority of whom seem to be of the opinion that these chloride salts are the chief cause of corrosion of automobile fenders and bodies.*[121]

The NCHRP report 577 [40] characterizes motor vehicle corrosion as atmospheric corrosion. Atmospheric corrosion occurs in the presence of oxygen and moisture. The presence of chlorides, however, accelerates atmospheric corrosion by increasing the conductivity of trapped moisture. Vehicle corrosion is categorized as either structural or cosmetic. The loss of integrity of brake components, undercarriage components such as frame members, and electrical components is considered structural. Staining and bubbling of paints are considered cosmetic, and affect primarily aesthetic appearance.

There are standard test methods for the study of corrosion of metals. One of the older methods that has been in use for over 70 years is ASTM B117, Standard Test Method of Salt Spray (Fog) Testing. It has been noted, however, that this test is not well correlated to real world conditions. Dan Szczepanik Original Equipment (OE)/ Commercial Projects Manager, Sherwin Williams, noted in a presentation to the CASE Study Committee on December 17, 2014, that a better cyclical corrosion test is ASTM D5894 (Standard Practice for Cyclic Salt Fog/UV Exposure of Painted Metal, [Alternating Exposures in a Fog/Dry Cabinet and a UV/Condensation Cabinet]) or SAE J2334 (Laboratory Cyclic Corrosion Test).[122] He stated that the latter is the only corrosion test specified by the Society of Automotive Engineers (SAE) that can use magnesium chloride or calcium chloride, because in other tests equipment corrodes and fails.

As part of data gathering for this study, several presentations were provided to the CASE Study Committee about corrosion of vehicles, particularly trucks. Some of these were informal and unpublished studies providing photographic evidence of (and sometimes actual) corroded vehicle parts. It was stated numerous times that *"it was noticed that corrosion increased starting around 2005, about the time that many states had started using magnesium chloride."* Most published documents about this topic are newsletters or trade magazine articles. There does not appear to be much published (peer-reviewed) research on quantitative studies of automotive or truck corrosion. It is stated in the FHWA report "Corrosion Costs and Preventive Strategies"[85] that vehicle manufacturers have made progress in corrosion prevention since the 1980s, but more work needs to be done specifically addressing brakes and electrical components.

It is worth noting that during the 2003-2007 timeframe there were several events and restrictions placed on industry by government that may also have contributed to an increase in corrosion potential. Around this time, Hexavalent Chromium (Chrome VI), which was used for many years as a corrosion inhibiting coating, was phased out as restrictions on its use became effective. In 2003, a directive was issued by the European Union (Directive 2000/53/EC) essentially banning the use of hexavalent chromium on all new vehicles and replacement parts sold after July 1, 2003.[123] Other vehicle manufacturers such as Ford followed with the elimination of the use of hexavalent chromium by 2007.[124]

The European Union's directive also pushed for both the elimination of cadmium in electronics as well as the incorporation of lead in metal to resist corrosion.[125] The elimination of cadmium, due to its corrosion resistance properties, from electronics, in particular electrical connectors, makes these components more susceptible to damage from corrosion. Also, the elimination of lead in certain metals for corrosion resistance also makes items such as gasoline tanks more susceptible to corrosion damage.

In a presentation to the CASE Study Committee on December 17, 2014, Bob Hamilton, Director of Fleet Maintenance for Bozzuto's, Inc., expressed concern about the observed increase in corrosion in Bozzuto's Truck Fleet of 250 power units and 500 dry van and refrigerated trailers. Bozzuto's truck fleet services IGA stores in 12 states. Hamilton described and produced photographic evidence of the types of corrosion involved, on parts that included: alternators, starters, cables and lights, brake shoes, brake chambers and landing legs, radiators, muffler support brackets, diesel fuel tanks, slider frames and frame rails, air shield support frames, suspension components, air tanks, battery boxes, electrical systems, steel wheels and cab floors. Photos from this presentation are included as Figures 6.10 through 6.14.

Some of the potential solutions presented by Hamilton to assist in combatting this corrosion include better monitoring (visual inspections) and data collection (documentation), maintenance changes, frequent equipment washing, use of more lubricants and anti-corrosive sprays (electrical sockets, pigtails, battery terminals, connections), vehicle material and specification changes (more aluminum, galvanizing, special paints, and undercoating), better warranty programs, and vehicle manufacturer involvement.[126]

FIGURE 6.10. CORRODED BRAKE COMPONENTS (PHOTO FROM [126])

FIGURE 6.11. NEW AND CORRODED MUFFLER SUPPORT BRACKETS (PHOTO FROM [126])

FIGURE 6.12. CORRODED AIR SHIELD SUPPORT FRAME (PHOTO FROM [126])

FIGURE 6.13. CORRODED LANDING LEG SCREW (PHOTO FROM [126])

FIGURE 6.14. SALT RESIDUE BUILDUP AND CORROSION (PHOTO FROM [126])

In another presentation to the CASE study Committee on January 21, 2015, Adam Hill, Vice President of Product Sales Engineering, Great Dane Trailers, indicated that the life of a truck trailer is highly dependent upon the level of maintenance performed. When little or no maintenance is performed, a trailer's life may be limited to 5–7 years. With occasional but ineffectual preventive maintenance, the life may be 7–10 years. However, proper preventive maintenance, including the repair of dents, gouges, scrapes, hinge repairs and any process to stop corrosion before it migrates, should lead to a trailer life of 20 years. However, trailers equipped with refrigeration systems are a controlling factor in that they are designed for 25,000 hours of use, and thus could limit the life cycle of this type of trailer to 8–10 years.[127]

Great Dane, which has been building truck bodies for over 100 years, manufactures refrigerated trailers, platform trailers, dry freight trailers and truck bodies. Finding components that are the weak link has been an important step for reducing corrosion and increasing the life of truck trailers. Electrical connectors are one such weak link identified by Hill during his presentation. Immersion tests were developed to test the corrosion mechanism and to quantify the levels of corrosion that can occur under the worst field conditions. This process led to re-design of electrical components.

Other changes that have been made in the design and construction of trucks and truck components as reported by Hill include: [127]

- more widespread use of stainless steel and galvanizing
- better coatings and application methods
- increased warranties on lighting systems

- improved barriers between dissimilar metals
- elimination of moisture harboring crevices in the truck bodies
- use of Magni™ coated fasteners to delay/prevent corrosion of bolts, screws and other fasteners
- use of CorroGuard, a spray-on protectant for metal, which was invented and marketed by Great Dane, for decreasing corrosion potential and thus increasing truck trailer life
- composite rather than wood subfloor cross members to prevent absorption of moisture
- use of plastic washers behind all screws, bolts, etc. to assist in prevention of chemical harboring

Stacey Spencer, Principal Engineer, Global Technology Specialist Materials Engineering, Volvo Group Trucks, a manufacturer of Mack trucks and several other truck vehicles in Europe and United States, made a presentation to the CASE Study Committee on March 11, 2015, on the "Effect of Deicers on Engineering of Class 8 Trucks." He reported that Volvo Group Trucks began conducting field studies in 1999 to monitor corrosion protection developments. The company has worked on development projects with material suppliers for steel, aluminum, coatings, and new technologies to address corrosion, as well as with organizations such as the American Trucking Association's Truck Maintenance Council, the SAE and the National Association of Corrosion Engineers (NACE). Field studies were performed that focused on the northeastern United States and Canada. A corrosion grading scale for monitoring the long-term corrosion of specific parts such as rear cab brackets, fasteners, and sheet metal, was developed. Their research conducted with other entities has led to development of coatings for sheet metals, galvanizing layers, pretreatments of surfaces such as chemical degreasing, and future products such as ceramic, zinc manganese and zinc manganese aluminum coatings. Volvo is working on developing computer software to allow prediction of electrocoating thickness based on design shapes; specifically, how to identify unwanted air pockets that prevent dip treatments from reaching areas that need to be coated for protection against corrosion. Volvo also developed and uses an accelerated corrosion test STD 423-0014 that replaces their use of ASTM B117 and other neutral salt spray tests that are less effective at correlating with field environments.[90]

6.4 HIGHWAY MAINTENANCE EQUIPMENT

The Western Transportation Institute at Montana State University is conducting a project for the Clear Roads organization, under the lead of the Minnesota DOT, titled, "Best Practices for the Prevention of Corrosion of Department of Transportation Equipment: A User's Manual" that is expected to be completed by mid-2015. The manual is based primarily on a study report on the same topic published in 2013 for the State of Washington. An abstract from the Washington report states,

> *this study has identified, evaluated and synthesized the best practices that can be implemented to minimize the corrosive effects of chloride deicers on DOT winter application equipment and vehicles. The practices identified include: design improvements, maintenance practices, anti-corrosion coatings, corrosion inhibitors, salt removers, etc.*[128]

The report's conclusions, some of which were also presented to the CASE Study Committee on October 21, 2014, by Monty Mills, Maintenance and Operations Branch Manager, Washington State DOT (ret), noted that preventive methods are proactive and can include:

- coatings
- use of corrosion-resistant materials
- dielectric grease
- enclosed wiring connections
- sacrificial anodes
- use of corrosion-inhibited products
- frequent washing of equipment

Mills noted that dealing with already established corrosion is reactive, but may be the most cost-effective strategy in some cases where parts are easy to clean, easily replaced or fairly inexpensive. Washington State DOT's estimated annual repair cost of maintenance vehicles due to corrosion is reported to be $417,000. It was noted that over half of this cost is for electronics and wiring, chassis and brakes. Some other types of repairs due to corrosion include repairs to engines, exhaust systems, fuel system components, drive trains, axles and hydraulics.[129]

All three chloride deicers—sodium chloride, calcium chloride and magnesium chloride—are used in various regions of the State of Washington. A study during 2003, referenced by Mills as the Washington salt pilot study, placed metal coupons along the edges of roadways to assess which type of deicer was most corrosive. The specific results were inconclusive. However, the study concluded that all salt solutions accelerate corrosion of steel and aluminum.

In order to slow or prevent corrosion, a number of modifications have been made to Washington State DOT's dump trucks and/or winter maintenance procedures.[129]

- valve bodies are enclosed in a stainless steel box with rubber gaskets
- batteries are enclosed in a sealed composite material box
- rubber covers are placed over battery terminals
- fuel tanks are aluminum
- oil pans are stainless steel
- electrical control units are placed inside the cab, and not near the floor
- rubberized undercoating is used on aluminum brake valves
- plastic quick release brake valves are used instead of aluminum
- salt and brine is spread only from the rear of trucks

Other suggestions from Washington State DOT include: [129]

- do not pressure wash vehicles as it may drive salt further into vehicle components
- keep truck frames coated, sandblasted and painted
- perform daily washing of trucks following any anti-icing activities
- re-apply dielectric grease to plugs and sockets as needed
- use a plug and socket brush with plain water (no soap) every six months to clean electrical connectors
- be cautious of using wash soaps that contain degreasers

During the course of this project, a number of similar maintenance and repair activities for vehicles and equipment were reported as being performed by CTDOT Maintenance, as well. A discussion of these repair activities is provided in Chapter 2, or in greater detail in the CTDOT report titled *An Overview of Snow and Ice Control Operations on State Highways in Connecticut* [4] (Appendix C).

6.5 METHODS TO MITIGATE AND/OR PREVENT CORROSION

Joseph Payer, University of Akron, noted in his presentation to CASE Study Committee in October 2014, that a reduction in corrosion on bridges and highways will require a move away from prescriptive, time-based strategies, to condition-based strategies. On existing bridges, a proactive approach is needed to minimize damage before the damage is significant. For new bridges, corrosion mitigation must be incorporated at the design stage. Life-cycle cost analysis that includes maintenance and preservation costs in addition to construction costs must be implemented.[89]

As noted previously, truck cab and truck trailer manufacturers such as Great Dane and Volvo are working at finding new materials and technologies to combat the effects of deicing chemicals since the use of such chemicals is unlikely to be reduced or discontinued anytime soon because of their effectiveness [90]

6.5.1 Use of Corrosion Inhibitors

Corrosion Inhibitor: *Any substance added in small amounts to a corrosive environment that effectively reduces the corrosion rate of a metal or alloy. Corrosion inhibitors tend to be metal and environment specific. No inhibitors retard corrosion significantly for all metals and alloys on all snow and ice control chemicals (*[40] *page 74).*

NCHRP study #577 states

> *Snow and ice control chemical corrosion inhibitors that are tested in the laboratory can show significant reductions in corrosion rates of the metals being tested, but they may show little or no inhibiting effect on other metals (even those in the same metal group) and may*

> *in effect accelerate corrosion of some metals. To develop any meaningful general corrosion rate data for deicing chemical corrosion inhibitors, tests must be run over a wide range of concentrations for both the corrosion inhibitor and the deicing chemicals, and also under a number of ambient conditions to simulate field conditions.* ([40]*page 76)*

Also stated in NCHRP #577

> *No literature was found that evaluated the effectiveness of corrosion inhibitors when used with snow and ice control materials at reducing corrosion of steel embedded in concrete.* *(*[40} *page 68).*

A laboratory study performed for the Iowa Highway Research Board in 2005 found that calcium chloride containing an inhibitor (tetraethanolamine) at 2,000 ppm delayed deterioration of concrete that was exposed to 38%–40% solutions of calcium chloride during freeze-thaw and wet-dry testing, but ultimately did not prevent it. In fact, the deterioration in the form of scaling, mass loss and reduction of compressive strength was ultimately worse for the inhibited solution compared to the uninhibited calcium chloride by the end of testing.[99]

The Western Transportation Institute (WTI) performed a comprehensive study of three inhibited liquid products for the State of Washington in 2010.[130] Laura Fay, Program Manager, Winter Maintenance and Effects, WTI, presented highlights of this study to the CASE Study Committee on November 14, 2014. Highlighted study conclusions included

- corrosion inhibitor concentration ranged from 20%-80% of the original application on the pavement surface four days after application
- corrosion inhibitors themselves did not improve anti-icing performance
- corrosion inhibitors did not degrade after 14 months of storage
- all three inhibitors tested (GLTTM, FreezGard CI PlusTM, and Boost CCBTM) had lower corrosion rates than salt brine
- one of the inhibitors suffered significant degradation from UV exposure
- one of the liquid brines containing a corrosion inhibitor, possibly due to extended shelf life, did not pass the corrosion score required by Pacific Northwest Snowfighters Association

The inhibitor to chloride ratio varies significantly by product sold. For instance, FreezGuard contained a ratio of inhibitor to chloride of 1–30, while the Boost CCB contained a ratio of 1–1.9, which was composed of 30.3% salt, 16.2% inhibitor, and 53% water. WTI noted that corrosion values from products applied in the field varied from values measured from the storage tanks. [130]

A review of corrosion inhibitor product information available online, such as Material Safety Data Sheets (MSDS), indicates that the content of inhibitors and additives that are found in many proprietary deicers are difficult to ascertain. The companies that produce and distribute these types of products typically protect their right of trade secrets regarding the ingredients included in their products. However, CTDOT, municipalities, and others have an implied responsibility to be aware of any environmental and other types of impacts from materials used for winter highway maintenance, especially due to the extent of coverage of deicers applied to over 20,000 lane-miles and uncountable acres of parking lots and other surfaces in Connecticut. The use of corrosion inhibitors for protecting infrastructure and vehicles, assuming these products are actually effective at reducing corrosion, may warrant consideration. However the possible environmental effects of the use of these products is also an important consideration.

There is interest in using corrosion inhibitors due to claims that these additives will protect or reduce corrosion of highway structures, as well as vehicles. The producers of the most common corrosion inhibitors test their products to ensure that they meet the Pacific Northwest Snowfighters (PNS) requirement that a deicer must be 70% less corrosive than rock salt in a controlled laboratory test (with controlled concentrations of deicer and corrosion inhibitor). PNS test methods (NACE Standard TM0169-95 as modified by PNS) are only used on specific steel coupons meeting ASTM F 436, Type 1, with a Rockwell Hardness of C 38-45. Motor vehicles, bridges and pavements are composed of many types of materials that are not necessarily covered by this corrosion test.

Dilution is another issue concerning the ultimate effectiveness of corrosion inhibitors. As chemicals melt snow or ice, they are diluted by water. Applying one gallon of any liquid to a 12-foot wide lane-mile is equivalent to applying one droplet of liquid per square foot of surface area, where one droplet is defined as 0.00219292052575 fluid ounces.[131] However, the chemical being applied during weather events is diluted from melted snow or ice, which unless the water can evaporate first, runs off of the edge of roadway. For this case, the amount of inhibitor remaining on the road after runoff is extremely small for each pass of an applicator truck that would be applying one gallon of inhibited salt per lane-mile.

As an example of the dilution that occurs when applying deicing chemicals, assume there is one lane-mile of road, 12 feet wide, with two inches of uncompacted snow on it with a snow to liquid ratio of 10:1. Converting the snow to water on this one lane-mile equates to 7,899 gallons of water. When the gallons are converted to weight using 8.34 pounds of water per gallon, this results in 65,877 pounds of water. In Connecticut, CTDOT treats roadways using one gallon of 30% magnesium chloride solution for pre-wetting 200 pounds of solid sodium chloride that is applied per lane-mile. For this example, it will be assumed that the gallon of magnesium chloride has 5% of an inorganic inhibitor added to it, and that all the water from the snow is completely mixed with the sodium chloride, magnesium chloride and inhibitor. Given these assumptions, the following concentrations can be calculated by weight:

- sodium chloride concentration 0.30%
- magnesium chloride concentration 0.0049%
- inorganic inhibitor concentration 0.00082%

6.5.2 Vehicle Washing

Removal of salts from vehicles is commonly a recommendation for preventing vehicle corrosion. In the simplest of methods this would involve washing all vehicle surfaces using water and detergents. A common observation has been that plain soap and water do not completely remove salt chemicals such as magnesium chloride from all surfaces. There are a number of chemical formulations that are marketed to assist in removal of salts and debris. These products are known as salt neutralizers, and generally work by changing the pH of the wash water and thus the materials on the surface that need to be removed. A change in pH theoretically allows for easier dissolution of the adhered chemicals.

Chelsea Monty, Assistant Professor, Chemical and Biomolecular Engineering, College of Engineering, University of Akron, provided a presentation to the CASE Study Committee on December 17, 2014, on a study she conducted titled *Effectiveness of Salt Neutralizers for Washing Snow and Ice Equipment*.[132] The study, performed in conjunction with Ohio DOT, surveyed and evaluated existing reports and experiences with salt neutralizers, performed laboratory experiments and performed a benefit/cost analysis on commercially available salt neutralizers. The survey found that approximately 55% of users felt neutralizers were effective. However, 80% of those users who tried and then stopped using neutralizers cited the expense of using the neutralizers as being too great.

The study also included testing of six proprietary salt neutralizers in the laboratory to determine their effectiveness. The results indicated that effectiveness was directly related to concentration levels. Some products actually increased the corrosion rate on some bare metals when used at manufacturers' recommended levels. The results indicated that neutralizers do not reduce corrosion for most coated metals. Many of the products were more effective when used at levels above those recommended by the product manufacturer. However, if used at higher concentrations, the cost effectiveness of such products would be reduced. The study included benefit/cost analyses on three of the best performing neutralizers, and determined that one product, "Salt-Away," was the most cost effective. The benefit/cost analysis found that a neutralizer can increase the life of an Ohio DOT maintenance truck by six months to a year if the truck is washed with a neutralizer 5-18 times per year.[132]

It is understood but not officially confirmed that many commercial car wash facilities in Connecticut use recycled water for both side and undercarriage water jets. Use of recycled water that may contain some level of salt during the winter season may be of concern for undercarriage washes as this may continue to expose the vehicle to conditions conducive to corrosion. A presentation provided by the Connecticut Car Wash Association to the CASE Study Committee in April 2015 provided an overview of typical car wash processes and techniques used in Connecticut, but did not provide any specific information regarding the treatment or processing of the recycled water or the use of salt neutralizers for undercarriage washes. Also, in April 2015, the National Highway Traffic Safety Administration (NHTSA) released findings of their five-year study into brake pipe corrosion that recommends washing the undercarriage of all vehicles in 21 states, including Connecticut, where the most winter deicers are used to prevent corrosion of critical components of brakes and suspension, particularly for model years 2007 and earlier. A NHTSA Safety Advisory was also issued.[133]

6.5.3 Bridge Cleaning

Literature indicates that several states remove debris and/or and rinse bridge structures to decrease chlorides. Several notable studies were conducted to determine the effectiveness of bridge washing, including those performed in Washington State, Ohio, Oregon, Kentucky, and Illinois. It is noted that the terms washing and rinsing may have been used interchangeably in some of these studies, but that generally rinsing involves only water, whereas with washing detergents may also be used. As noted in Chapter 2, CTDOT conducted a pilot bridge rinsing project on a very limited basis that ended in 2012. This pilot was conducted in accordance with DEEP designated guidelines that included rinsing, at specific times of the year, on 25 CTDOT bridges that do not cross waterways.[4]

A study conducted on behalf of the Washington State DOT by the Washington State Transportation Institute, University of Washington, with an objective to identify the key variables necessary in estimating the impact of regular washing of steel bridges on the paint and service life, concluded "*that little information on the effects of bridge washing exists and it is only deemed beneficial based on anecdotal assumptions*".[134]

Another study by the same authors was performed to "*examine the perceived costs and benefits of routine washing of both steel and concrete bridges, with emphasis on substructure seats and bridge decks, by exploring current practices around the U.S.*".[135] This study also included a formal survey of other states. One question asked was "*How frequently are steel and/or concrete bridge deck surfaces, expansion joints, and/or bridge bearings cleaned?*" The results indicated that the majority of states either wash bridges at least once every two years (15 states), or not at all (17 states). The impact on bridge component life due to the cleaning of decks, bearings or expansion joints was not studied by any of the responding states. Of the 34 state DOTs who responded to the survey, approximately 10 never clean expansion joints or bearings. The survey results indicated, however, that the cleaning of expansion joints and bearings is given higher priority than bridge decks in all regions. Northeast states indicating they cleaned or washed bridges included: Maine, New Hampshire, New York, Pennsylvania, and Vermont. Also, Maine and Pennsylvania indicated they wash decks annually. Connecticut did not participate in the survey. [135]

A study conducted by Oregon DOT [136] was undertaken to investigate the efficacy of washing bridges to reduce existing chloride content and chloride ion uptake. The report indicated:

> …*component test sections of a coastal bridge were pressure washed on a once per year and twice per year schedule. Field testing was discontinued after two years because the laboratory results indicated that the washing frequencies used on the bridge were much too low to produce any change in chloride levels. After four years, the laboratory trials showed that daily washing with fresh water can appreciably reduce the ingress of chloride ions, but occasional washing is ineffective.*[136]

It must be re-emphasized that the bridges washed in this study from 2000-2005 were near ocean maritime environments (i.e., not just bridges that were treated for winter storms.)

In another 1991 publication [137] it was stated that

> *Franklin County, Columbus, Ohio, has been flushing all of its bridges, including unpainted weathering steel bridges and coated bridges for 8 years. The objective is to remove all deicing salt residue, dirt, and debris from the bridge deck, drainage system, and beam seats of all bridges, and so eliminate corrosion and scaling. It is noted that it is impossible to determine the cost effectiveness of the program, and only long-term repair and replacement rates will show the program's worth.*[137]

The Kentucky Transportation Center, College of Engineering, University of Kentucky, in cooperation with the Kentucky Transportation Cabinet, conducted a study titled "Investigation of Soluble Salts on Kentucky Bridges" in 2002 [138]. This study was initiated

> *to investigate the presence of soluble salts on Kentucky bridges and to determine if they pose a significant problem to bridge paint durability. The objectives of the study were to:*
> 1. *Determine the levels of soluble salts on Kentucky bridges;*
> 2. *Study the effect of various cleaning methods (pressure washing, power and hand tool cleaning, etc.) on soluble salts on bridges; and*
> 3. *Establish whether commercially available chemical neutralizing/soluble salt removing agents are capable of reducing salt levels to where they will not damage new paint nor cause early "rust back."*
>
> *The tests of three bridges revealed low levels of soluble salts in most instances, even in the untreated or "existing conditions." Pressure washing with potable water was effective in reducing the amounts of soluble salts as was pressure washing with CHLOR*RID (Trademark). The testing did not reveal a significant problem related to soluble salts, but the testing was too limited to make a determination about all Kentucky bridges.[138]*

In 2002, the Rhode Island Department of Transportation performed a study of the DOT bridge program that looked at washing bridges to "*improve the occupational safety of RIDOT bridge inspectors, allow thorough inspection of bridges and to reduce corrosion due to salt application*."[139]

The study report states that

> *washing bridges is an integral part of an effective bridge inspection program. Inspection of a bridge without sand, mud, salt, bird droppings, bird nests and other debris is much more effective. Washing also addresses a major health and occupational safety concern, as bird droppings and nests can present a health hazard to bridge inspectors. …. It is also recognized that applying salt to bridge decks increases rusting and degradation of concrete. Washing bridges after the winter season can significantly extend bridge life.*[139]

6.5.4 Protection for Structures

In order to protect structures from the effects of deicing chemicals, there are many steps that can be taken for steel bridges and concrete structures, as follows:

- For steel bridges, these actions include:
    - maintaining proper coatings on exposed steel members within the bridge
    - ensuring that the bridge joints are in good condition and minimize water infiltration
    - periodically cleaning the structures to remove chlorides, as well as other debris that may hold moisture and allow corrosion to occur
- For concrete structures, these actions include:

- using polymer concrete for thin bonded repairs of bridge decks
- ensuring proper concrete cover for steel reinforcement
- using corrosion inhibitors in concrete itself and incorporating high-density/low-permeability concretes to minimize chloride penetration into designs
- using epoxy-coated steel, ensuring that any damage that is detected during the placement of the steel is repaired before placing the concrete
- for high-volume structures, consideration should be given to using stainless or galvanized steel for reinforcement
- using cathodic protection installations for prevention of steel reinforcement corrosion
- using high molecular weight methacrylate for sealing cracks in concrete bridge decks

In addition, some states have been using silanes to seal their concrete bridge decks. The Oklahoma DOT is one of a few states that has studied coating bridge components with silane.

> *The performance of a generic silane penetrating water repellent material was evaluated using alternate test procedures. Two basic laboratory tests series were used: 1) Oklahoma Department of Transportation tests, and 2) a series based on NCHRP 244 Series II. Silane performance was evaluated with respect to depth of penetration, absorption, water vapor permeability, and chloride ingress. Results indicated the need to represent field conditions (particularly mix design) to the extent possible in order to predict better field performance with laboratory tests. Also, relative performance of some mixes was affected by the test procedure performed.*[140]

A number of techniques, including some recommended in other studies that are cited in this chapter, have been or are currently used by CTDOT. Cathodic protection (CP) was utilized on several existing CTDOT bridges that underwent deck repairs during the 1990s under a research project that is still underway. The objectives of the project are to monitor the installation of various anode systems on structures in Connecticut's highway system; obtain installation costs and operating power usage of alternate anode systems; monitor the operating characteristics and effectiveness of each type of anode system; and continue monitoring all existing CP systems on CTDOT structures.

Also, information provided by CTDOT Bridge Safety and Evaluation staff indicates that the department currently specifies high performance concrete and latex modified concrete for new decks, and membrane waterproofing and asphalt overlays are applied routinely for deck rehabilitation. Various corrosion-resistant reinforcing bars, such as epoxy coated, MMFX, stainless steel clad, and galvanized, are used where appropriate. MMFX is microcomposite steel that is highly corrosion resistant and equal, or superior to conventional carbon steel properties.

6.6 IMPLICATIONS AND CONCLUSIONS

It is noted that the research conducted for this study shows that there is a foundation of quality basic research on corrosion of steel, but less certainty regarding the effects of salts on concrete. Additionally, it is noted that sodium chloride comprises 99% of deicing chemicals applied by CTDOT.

Collectively, the laboratory studies cited in this chapter indicate that sodium chloride is less damaging to concrete pavements than magnesium chloride or calcium chloride. This finding has not been positively confirmed with field studies. However, one field study conducted in Oregon did conclude that sodium chloride is less damaging to concrete bridge decks.

There is no doubt that chemicals used for winter highway maintenance accelerate corrosion of Connecticut's infrastructure, and bridges in particular. However, it is virtually impossible to determine the precise extent to which chlorides contribute to the corrosion process. Connecticut's bridges are in a similar condition to — but with fewer poor rated bridges —than many nearby northeastern states.

Additionally, little evidence was found that corrosion inhibitors that are added to chemicals used for winter highway maintenance reduce corrosion of infrastructure or vehicles.

There are ways to combat or at least slow the inevitable process of corrosion. Some involve the use of the latest technologies and materials. A number of studies conducted by other states suggest, but do not prove, that the rinsing of bridges has the potential to aid in slowing the corrosion process of existing bridges. Prompt washing of trucks and motor vehicles after snowfalls can reduce corrosive effects of all salts that are used, and will likely continue to be in use for the foreseeable future.

7.0 BEST PRACTICES AND NEW TECHNOLOGIES

This chapter provides information regarding the best practices for winter highway maintenance operations as well as new technologies that are available to enhance these activities.

7.1 BEST PRACTICES

Sustainable winter maintenance operations are achieved by balancing the demands of the users, the available budget, and the environment. There are many examples of best practices that can be considered to achieve these sustainability goals:

- Provide for the safety of the public as much as possible during and following a winter weather event
- Provide the highest level of service possible for the current conditions
- Maximize the effectiveness of winter highway operations through the efficient use of human resources, appropriate equipment and technologies, and by using only the quantity of materials necessary based on event conditions
- Minimize the impact on the environment

The most environmentally friendly method for clearing snow and ice from roadways is to mechanically remove as much of the snow and ice as possible by plowing before using deicing chemicals. Anti-icing strategies enhance the effectiveness of plowing by preventing snow and ice from bonding to the pavement, thereby reducing the amount of deicing chemicals required to make a roadway safe to travel after a winter weather event. One aspect of the anti-icing strategy that is often overlooked is educating the public on the importance of pre-treating roadways to prevent snow and ice from adhering to the road. Whether the pre-treating is done several days in advance with a liquid sodium chloride brine or with solid materials just before the winter weather event has begun, the general public may perceive anti-icing/pre-treating as being wasteful, believing that the materials applied to the roadway will be plowed off on the first pass instead of actually improving the ability to clear the roadway of snow and ice.

CTDOT has implemented most of the best practices identified in the 2006 CASE study on winter maintenance, including:

- Adopting an anti-icing strategy including pretreating roadways with liquid sodium chloride brine in advance of a winter weather event
- Applying deicing chemicals early in the winter weather event to prevent the snow and ice from bonding to the pavement
- Eliminating the use of sand
- Purchasing trucks with variable-rate material-dispensing capability

Connecticut's municipalities have also adopted, in varying degrees, many of the best practices outlined in the 2006 CASE report. CTDOT and a majority of municipalities report calibrating their material spreaders at least annually, if not more often, which helps to ensure that the desired amount of materials are being applied.

The Center for Environmental Excellence by the American Association of State Highway and Transportation Officials (AASHTO) conducted a survey of winter maintenance practitioners. Fifty percent of the respondents reported that technologies, tools and methods implemented in the last 10 years were intended to reduce the cost of winter maintenance activities. Respondents also reported that these changes ultimately resulted in a reduction in the amount of materials that need to be applied to maintain the same (or improved) level of service. Table 7.1 indicates the top ten practices identified by the survey respondents.[141] A comparison of the practices employed by CTDOT, as well as many of Connecticut's municipalities, shows that most of the practices listed in Table 7.1 are being utilized.

TABLE 7.1. TOP 10 PRACTICES IDENTIFIED BY SURVEY RESPONDENTS
AASHTO'S CENTER FOR ENVIRONMENTAL EXCELLENCE (SOURCE: REFERENCE [141])

1	Anti-icing
2	Pre-wetting
3	RWIS
4	Brine Production
5	Staff Training
6	Monitoring and Keeping Records of Maintenance
7	Pavement Temperature
8	Equipment Calibration
9	Deicing
10	Material Storage

There is a need to track the amount of material being placed on each plow route for each winter weather event. This information can be used to track the amount of material that is applied by each operator on each route. If the data show that operators have applied materials at either a higher or lower rate than the target rate, the cause can be researched and adjustments can be made accordingly.

Each agency should develop guidelines for the application of materials for anti-icing and deicing. These guidelines should identify historically problematic areas as well as environmentally sensitive areas. It is important to periodically (annually at a minimum) review these guidelines to keep them current and incorporate changes as appropriate. The guidelines should include training requirements about the different deicers and the best practices for their application for equipment operators. The training should also cover changes in equipment and technology that directly impact the agency's winter highway operations.

Communication between agencies is an important tool on both the state-to-state level as well as on the state-to-municipality level. In preparation for and during winter weather events, CTDOT communicates with neighboring states about the conditions each state is experiencing. CTDOT utilizes information from surrounding states to obtain as much lead time as possible to mobilize people and equipment in advance of the onset of the event and prior to deterioration of road conditions. As most winter weather approaches Connecticut from the west or the south, communication with states such as New York and New Jersey helps provide CTDOT with the appropriate mobilization lead time. Similarly, communicating with Massachusetts and Rhode Island about conditions in Connecticut is beneficial to those states. While CTDOT and the municipalities communicate regularly through many different channels, including local maintenance garages, CTDOT could also make information available to the municipalities from their existing RWIS. According to the Federal Highway Administration's Office of Operations, RWIS stations provide valuable data for winter weather event management and decision making. [142] These data include

- air temperature
- wind speed
- type of precipitation
- rate of precipitation
- pavement surface temperature
- condition of the pavement surface (wet, slushy, snow covered, icy)
- concentration of chemical deicer on the pavement surface
- calculating the freeze point of water given the concentration of deicing chemical present

While this information is literally a snapshot of current roadway conditions at the RWIS station, it provides another tool for municipalities in the general vicinity of the RWIS station to use in their decision-making process. This capability will be enhanced as additional RWIS stations are added to the CTDOT RWIS station network, with the expectation that the new RWIS stations will also have the capacity to provide state-of-the-art, weather-related information. Connecticut's entire RWIS station network helps to provide real-time data to centralized locations from remote areas throughout the state.

Ideally, making the RWIS information available to both state and municipal entities throughout the Northeast would be a significant benefit. As most of the states are small, information from surrounding states would be beneficial for locales bordering each other. The Federal Highway Administration and the National Weather Service have a service, the Meteorological Assimilation Data Ingest System (MADIS) (https://madis-data.noaa.gov/MadisSurface/), that can be used to upload RWIS data and make it publicly available. At this time, New Hampshire DOT appears to be the only regional transportation agency uploading RWIS data into the MADIS system.

Communication with the public is also key to having a successful winter highway maintenance program. This outreach would include providing information about the deicing chemicals being used, quantities of these materials used in previous years along with explanations of the winter highway maintenance practices observed by the public, such as pre-treating with sodium chloride brine. This information should be made readily available on the CTDOT website. The development of winter indices should be considered for a variety of purposes related to winter weather events and winter highway maintenance operations.

- A winter severity index would be very helpful to make comparisons between winter seasons. This would help managers understand winter highway maintenance operations performance with regard to use of materials and labor on a season-wide scale. A winter severity index would also provide a basic understanding and documentation of unusual weather events that caused an unusually high amount of materials or labor to be used in an event or winter season as compared to another.
- A CTDOT winter weather event or road condition index would enable CTDOT to convey to the public the degree of impact that a forecasted winter weather event will have with regard to transportation. This winter storm index rating or score could vary throughout the state depending on the type of winter weather event expected as well as the varying micro-climates within the state. In addition, CTDOT could use speed and flow data along with data from the RWIS stations to convey real-time road conditions to the public during a winter weather event.

7.2 NEW TECHNOLOGIES

7.2.1 Ground Speed Controls for Deicing Material Spreading Equipment

Ground speed controls adjust the application rate of material applied to the road based on the speed of the truck applying the material. Therefore, ground speed controls should be used to ensure that the proper amount of material is being applied. This technology helps equipment operators because it eliminates the need for the driver to constantly adjust the application rate based on the speed of the truck. This technology has been available for some time, and is now standard on CTDOT vehicles. Many municipalities have also included ground speed controls on their equipment. However, some municipalities do not use this technology, and would benefit from including ground speed controls when purchasing new vehicles.

7.2.2. GPS Tracking (Automatic Vehicle Locator Systems) and Data Logging

The use of GPS tracking of winter highway maintenance vehicles provides managers with data and information to periodically review plow routes and cycle intervals between treatments to ensure maximum efficiency. In addition, the technology exists to monitor application settings used in the vehicles. The data reported by this system provide a good estimate of the amount of material applied. However, this information may not represent the exact amount of material applied as there may be other factors, such as clogged chutes or conveyors not functioning properly, that may impact the amount of material applied. An agency’s considerations for adopting the use of this type of technology include the following:

- The system produces a large amount of data that need to be analyzed for use
- Post-winter weather event analysis is needed for use in decision making

- Before adopting this technology, an agency should make sure they have a plan for how the data will be processed, analyzed and used for decision making

7.2.3 Salt Slurry Application Trucks

Salt slurry trucks carry solid and liquid deicers. Typically, a small crushing unit installed on the truck reduces the effective size of the salt crystals. The crushed salt crystals are mixed with the liquid deicer to make a material with an "oatmeal like" or "slurry" consistency before it is applied to the roadway. The expected benefits of this application method are as follows:

- The slurry comprises a considerable liquid component, which is essential for starting the melting process of snow and ice.
- The consistency of the slurry applied to the roadway prevents the material from bouncing and scattering. This reduces the amount of material needed for treating the road surface since most of the material is maintained in the travel lanes.
- The smaller salt crystals have a much greater surface area, which improves the rate of dissolution as it comes into contact with water.

CTDOT purchased three salt slurry generators as a trial to determine their effectiveness and whether to integrate their use in regular winter maintenance operations. CTDOT first experimented with a salt slurry generator in 2013. Two additional salt slurry generators were delivered to CTDOT later than expected, near the end of the 2014-2015 winter season. Late delivery, along with the complexity of installing the units, made it difficult to make the necessary adjustments required for proper operation this past year. However, CTDOT plans to have these issues resolved before the start of the 2015-2016 winter season. Therefore, a decision on integrating their use into the department's winter maintenance operations will be delayed until completion and analysis of the results of the trial.

7.2.4 Underbody Scraper Blades (Belly Snow Plows)

The use of snow plows mounted under the truck, between the front and rear axles, allows for much greater downward pressure for scraping the pavement surface. This is particularly helpful for the removal of snow and ice pack that has built up on the roadway.[143] This style of snow plow does not eliminate the need for snow plows on the front of the truck, as underbody scraper blades are not designed to push back the edges of the snow banks. While it is neither desirable nor practical to install underbody scrapers on all of the trucks used to plow snow, having this option available may be beneficial for specific situations.

FIGURE 7.1. UNDERBODY SCRAPER BLADE IN THE UP POSITION
(COURTESY MERIDEN, CT DPW)

7.2.5 *Multi-Sectional Snow Plows*

Multi-sectional snow plows allow smaller subsections of the plow blade to move a small distance up or down to better conform to the pavement's cross-section. This type of plow is most beneficial on roads that have wheel path rutting where a solid steel plow blade would bridge across the high spots on the pavement and not be able to adjust to the pavement configuration.[144] Multi-sectional snow plows may be of particular interest to municipalities where their roads have the most cross-section variability.

FIGURE 7.2. MULTI-SECTIONAL SNOW PLOW (COURTESY MERIDEN, CT DPW)

7.2.6 Truck-Mounted Pavement Temperature Sensors

The use of truck-mounted pavement temperature sensors provide equipment operators with information about pavement temperature. Pavement temperature information can then be used by the equipment operator to make decisions about whether or not the application of deicing chemical is needed, as well as to possibly adjust application rates when it is used. Pavement temperature sensors are becoming more common in winter maintenance truck fleets in Connecticut and should be considered for all new vehicles that are purchased.

FIGURE 7.3. AIR AND PAVEMENT TEMPERATURE SENSOR (COURTESY IOWA DOT)

FIGURE 7.4. AIR AND PAVEMENT TEMPERATURE SENSOR DISPLAY (COURTESY IOWA DOT)

7.2.7 Front End Loader Weighing Systems

Technologies have been developed to attach load cells to the bucket on front-end loaders that weigh the amount of material in the bucket. This technology can be used to record the amount of material being loaded on each truck before it begins its route during a winter weather event. At the end of the winter weather event, the amount of material that remains on the truck is unloaded and weighed. The amount of material used by a truck during the winter weather event is then calculated from the data collected. This type of system can provide agencies with an accurate record of the amount of material applied during a winter weather event, as well as for entire winter weather season.

8.0 WINTER HIGHWAY SAFETY ANALYSIS AND OVERVIEW OF ECONOMIC AND SOCIETAL IMPACTS

As previously discussed in Chapter 2, between 2006 and 2007 CTDOT transitioned from a deicing to an anti-icing strategy. This change resulted in greater efficiencies in removing snow and ice from roadways. It also improved surface conditions by providing safer driving conditions along the state highway system much sooner following a winter weather event (activity or storm). Anti-icing strategies also reduce the number of re-freezing occurrences following a winter weather event.

Safety benefits of anti-icing strategies have been reported in several states. According to a brochure published by the Pacific Northwest Snowfighters Association "*Snow and ice control methods have had a major, positive impact on traveler safety. In a case study in Iowa, it was found that during severe winter weather events, accidents increased by 1,300 percent and traffic volume decreased by 29 percent on a 30-mile roadway segment. In the State of Washington, it was found that the crash frequency rate was five times higher in the presence of snow than under clear roadway conditions…… During a twelve-year study involving anti-icing strategies on the interstate system in the Denver metro area, Colorado saw an average decrease of 14% in snow and ice related crashes.*"[145]

8.1 CONNECTICUT VEHICLE CRASHES WITH INJURIES

The Connecticut Crash Data Repository (CTCDR) maintained at UConn's Connecticut Transportation Institute was used to perform crash analyses for this study. The CTCDR contains all crashes that occurred within Connecticut on both the 3,734 centerline miles of state-maintained and the 17,339 centerline miles of municipal-maintained roadways.[5] The crashes recorded in the CTCDR involve property damage, and personal injuries and/or fatalities that are reported and investigated by a local or state law enforcement agency. Approximately 1.5 million crashes are currently included in the CTCDR on all types of roadways for the years 1995 through 2013. The CTCDR crash data can be retrieved, sorted and summarized by any number of attributes, such as location (route, town, region); collision type; date; time; weather condition; road surface condition; light condition; and several other attributes.[146]

This study used only crashes that occurred on the state highway system, which includes interstates, US routes and Connecticut routes. Excluding municipal roads eliminates the variable of differing winter maintenance policies and procedures utilized by Connecticut's 169 cities and towns. The winter maintenance policies applied to state roadways are consistent throughout Connecticut, with the primary variables being traffic levels and local climatic conditions. Finally, to ensure enough crash data for analysis, retrieved crashes were analyzed statewide rather than by weather region or CTDOT Maintenance District.

Figure 8.1 contains a plot of all the injury-only crashes that occurred in Connecticut on state roadways (no town roads are included) for all months of each year for calendar years 2000 through 2013. This graph includes data for 247,988 crashes. The vehicle crashes in Figure 8.1 occurred under all possible pavement surface conditions, i.e., dry, wet, snow, slush, ice, sand, mud, dirt or oil, other or unknown. Crashes occurring under all weather conditions were also included in the data extraction.

Figure 8.1 shows a consistent reduction in crashes involving injuries for nearly every year plotted relative to the previous year. One possible explanation for the significant reduction in crashes over this 14-year period might be improvements in vehicle safety technologies (e.g., anti-lock brakes, air bag restraints, tire tread design, stability control, traction control, all-wheel drive) and an increase in the number of newer vehicles containing these safety technologies (or conversely, a reduction in older vehicles without them).

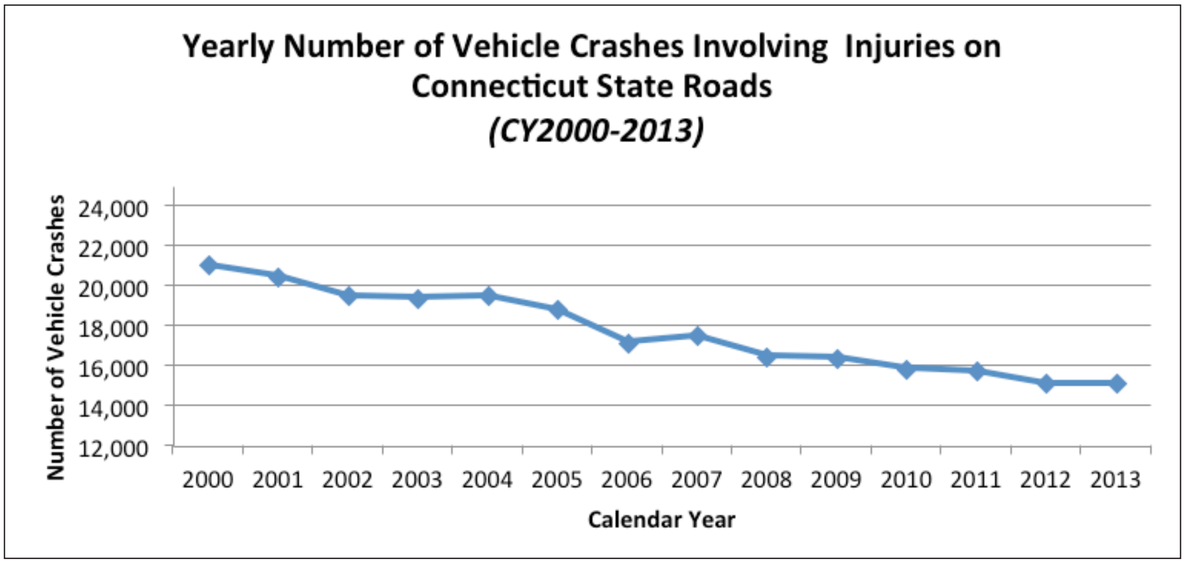


FIGURE 8.1. YEARLY NUMBER OF VEHICLE CRASHES INVOLVING INJURIES ON CONNECTICUT STATE ROADS (CALENDAR YEARS (CY) 2000 – 2013)

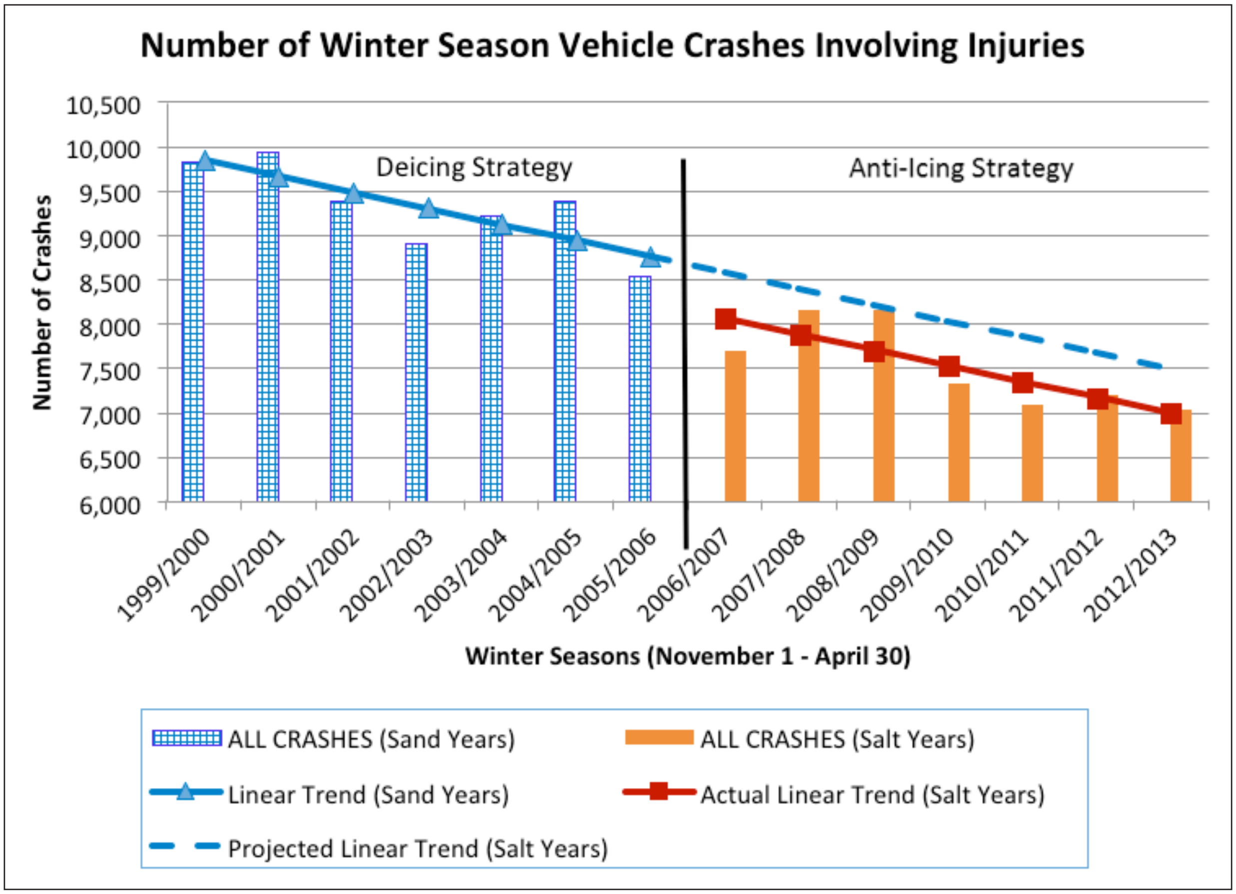
8.2 WINTER WEATHER VEHICLE CRASHES

Winter season vehicle crashes that include injuries were selected as a possible measure to determine the impact of the effectiveness of CTDOT’s change to an anti-icing strategy. On a positive note, when the pavement condition is compromised from snow, slush or ice conditions, the number of crashes involving fatalities is typically very small and not representative. Therefore these crashes were not considered for this analysis. During winter weather events, law enforcement personnel need to prioritize their response to many near-simultaneous crashes, with those crashes involving injuries typically receiving the most attention. Thus, even though property damage only-type crashes are much more prevalent, it is believed that the information recorded about winter-weather property-damage-only crashes would tend to be less reliable, particularly during periods when hundreds of crashes occur over a short timeframe. Therefore, it was determined that crashes with injuries only were the best metric to use for gauging the effectiveness of the change in safety regarding CTDOT winter highway operations.

Key variables associated with winter weather events that can affect the number of vehicle crashes that occur during periods when snow, slush or ice conditions exist on the pavement surface, include the following:

- Vehicle speeds during a winter weather event
- Vehicle miles traveled during a winter weather event
- Winter weather event duration and snowfall rate variability
- Extent of deployment of motor vehicle safety technology
- Day of the week and time of day of the winter weather event
- Forecasted strength of the event
- Solar influence (varies throughout the year as the sun angle changes) as well as how long the cloud cover stays after the event
- Air and ground temperatures
- Wind speed and direction
- Actual pavement surface conditions that may differ from the condition reported on a crash report
- Overall physical pavement condition, (e.g., pavement surface texture, presence of potholes)

While some of these variables can be taken into account, given the information that is available, it is not possible to account for all or even most of them. Therefore, the crashes involving injuries that occurred during times when the surface of the pavement was reported by responding police officers as snow, slush or ice covered was selected as the best methodology to use in this report’s safety analysis. Relative to crashes with injuries, crashes with fatalities are few in number, and as mentioned previously, are excluded from the analysis.



Crashes shown are extracted from the CTCDR using the following conditions:

- CTDOT only database (i.e., not police database)
- Months of: November, December, January, February, March, April only
- State routes, interstate routes, US routes (no local roads)
- Injury crashes only (No property damage only and no fatal crashes)
- Weather conditions = ANY
- Surface Conditions =ANY (wet, dry, snow/slush, ice, sand, mud, dirt or oil, other or unknown)
- All other attributes such as contributing factors, collision types, light conditions, etc. were set to ANY

FIGURE 8.2. WINTER SEASON VEHICLE CRASHES INVOLVING INJURIES:
1999/2000 – 2012/2013

To begin the analysis, Figure 8.2 shows a graph of all crashes with injuries that occurred from November 1 – April 30 for 14 winter seasons since 1999/2000. Linear trend lines for both the deicing strategy years when sand and salt were used in a 7:2 ratio (seasons 1999/2000 - 2005/2006) and the anti-icing strategy years when only salt (little or no sand) was used (seasons 2006/2007 – 2012/2013) are included. As shown in Figure 8.2, the deicing strategy trend line when projected forward is nearly parallel to the actual trend line for the anti-icing strategy years. However, the anti-icing strategy years' actual trend is approximately 500 crashes lower than the projected trend. Using this information alone, for the 117,890 vehicle crashes with injuries (on state roads only) included in Figure 8.2, suggests that the anti-icing strategy was responsible for an additional decline in the number of winter weather crashes involving injuries beginning in the winter season of 2006/2007.

8.2.1 Snow/Slush/Ice Surface Crashes

It can be hypothesized that with better pavement traction sooner following a winter weather event, and in some cases even during the event, Connecticut's anti-icing strategy should promote safer driving conditions, leading to an overall reduction in vehicle crashes during the winter season. To test this hypothesis, highway crashes that occurred on pavement surfaces of snow, slush or ice during both the deicing strategy years (1999/2000 through 2005/2006) and anti-icing strategy years (2006/2007 through 2012/2013) were analyzed. Also, only crashes that occurred from November 1–April 30 each year were included in the analysis. (Note: Crash data for 2014 were not available for inclusion in the analysis in this study.) As shown in Figure 8.3, these data indicate that the number of vehicle crashes involving injuries on surface conditions of snow, slush or ice for the period of 1999/2000–2012/2013 is 12,199, with roughly 200–1,400 crashes per season.

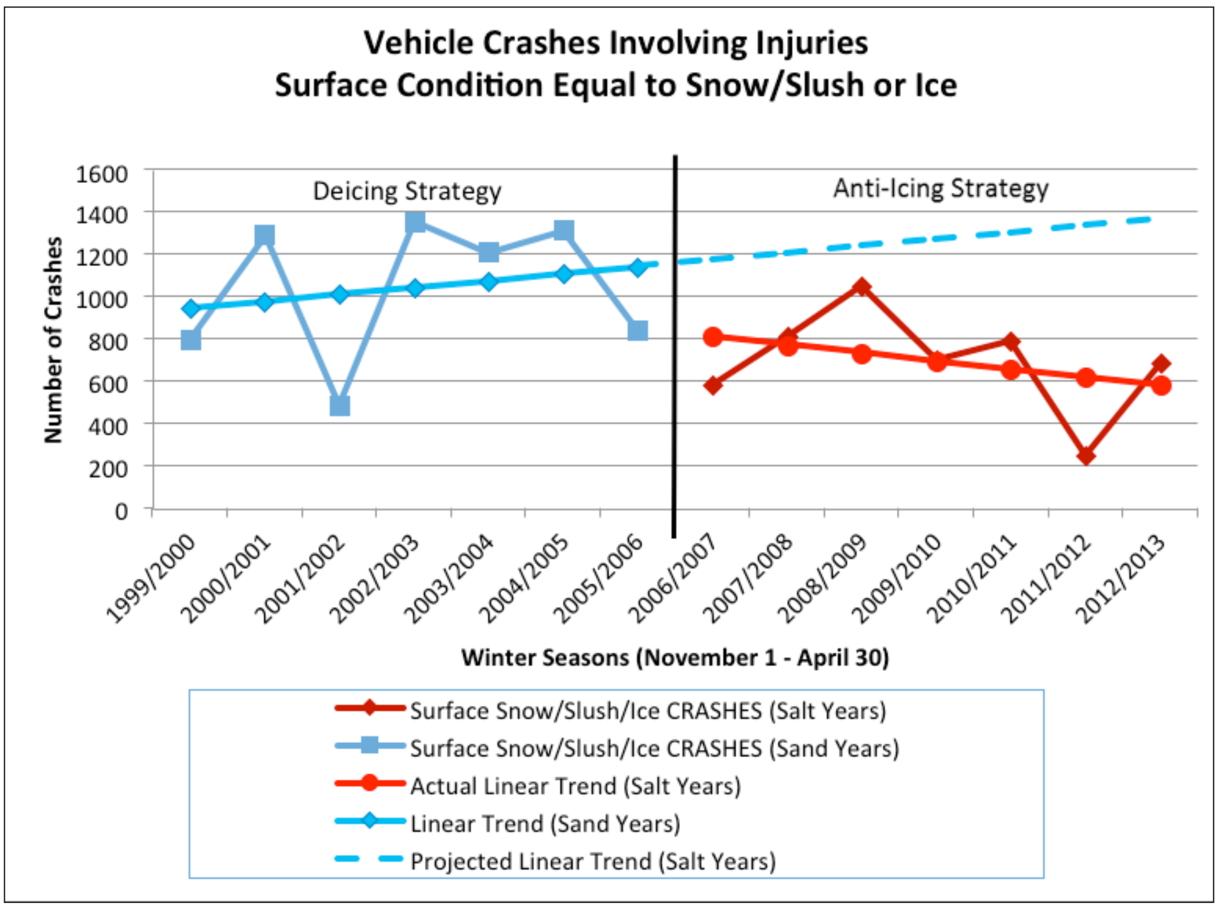


FIGURE 8.3. VEHICLE CRASHES INVOLVING INJURIES, WITH SURFACE CONDITION EQUAL TO SNOW/SLUSH OR ICE

A linear trend line for the deicing strategy period is superimposed on the graph in Figure 8.3, as well as projected forward through the anti-icing years. A second linear trend line is placed over the salt only years (anti-icing period). It can be seen in Figure 8.3 that the trend for vehicle crashes with injuries under surface conditions of snow, slush or ice for the deicing years was upward. However, after the implementation of anti-icing strategies, the actual plotted trend for these types of vehicle crashes has been downward since the winter season of 2006/2007.

Additional information on the average reduction in crashes is presented in Table 8.1. As previously indicated, these values are based on injury-only crashes. There was a 19.2% reduction between the average number of crashes during the deicing and the anti-icing periods for all injury crashes as plotted in Figure 8.2, but an even greater reduction of 33.5% for the crashes when the surface road condition is listed as snow, slush or ice (from Figure 8.3). Thus, the reduction in surface snow, slush or ice crashes was significantly greater than just the general crash reductions that occurred between these two time periods.

TABLE 8.1. DIFFERENCE IN AVERAGE NUMBER OF CRASHES WITH INJURIES FOR DEICING AND ANTI-ICING TIME PERIODS

Winter Season Months *(November, December, January, February, March, April)*	**A** *Deicing Years* (1999/2000 through 2005/2006)	**B** *Anti-icing Years* (2006/2007 through 2012/2013)	**A-B**	**(A-B)/A**
	Average number of crashes per winter season over 7 seasons (Sand and Salt years)	Average number of crashes per winter season over 7 seasons (Salt only years)	Change in average number of crashes between deicing and anti-icing years	Percent change in average number of crashes
All crashes with injuries	9,314	7,527	1,787	-19.2%
Crashes with injuries when road surface contained snow/ slush or Ice	1,046	696	350	-33.5%

Improvements in vehicle technology, as previously noted in the discussion on Figure 8.1, undoubtedly have produced favorable injury crash reductions. Additionally, CTDOT winter maintenance policies have likely contributed to these reductions when winter weather surface conditions are considered. Also, it is expected that anti-icing techniques reduce the number of hours that roads are snow, slush or ice covered, thus reducing the opportunity for these types of crashes to occur. Data on actual numbers of hours that roads are snow, slush or ice covered per year were not available for this study. The number of winter weather events per season however, was recorded as reported by CTDOT (see Chapter 2), and snowfall is discussed in the following section.

8.2.2 Snowfall Variability in Connecticut

Much of the year-to-year variability in vehicle crashes shown in Figure 8.3 is related to the number of winter weather events. For example, the low number of crashes during 2001/2002 and 2011/2012 is probably related to the lower number of winter weather events that occurred in those two seasons.

CTDOT measures and records snowfall at 26 locations in Connecticut during each winter weather event. Connecticut is a small state, ranked 48th in size with 4,845 square miles, with an approximate 2,000 ft. elevation differential between Long Island Sound and portions of Litchfield County. With the significant variation in elevation, as well as location relative to Long Island Sound and the Atlantic Ocean, there are wide variations in the severity of the winter weather experienced throughout the state during any given winter weather event.

Much like the crash rate during surface conditions of snow, slush or ice, Connecticut average snowfall (the midpoint of the range of snowfall measured by CTDOT at the 26 locations) for winter seasons 2000/2001 through 2012/2013 demonstrates a large year-to-year variability (Figure 8.4). A linear trend line that is also overlaid onto Figure 8.4 shows that even though the average snowfall amount varies significantly from year to year, the long-term trend has been rather steady. Another way to denote this is that the average annual snowfall for the six winter seasons when deicing was used (2000/2001–2005/2006) is 51 inches, and for the later seven years of anti-icing is 42 inches.

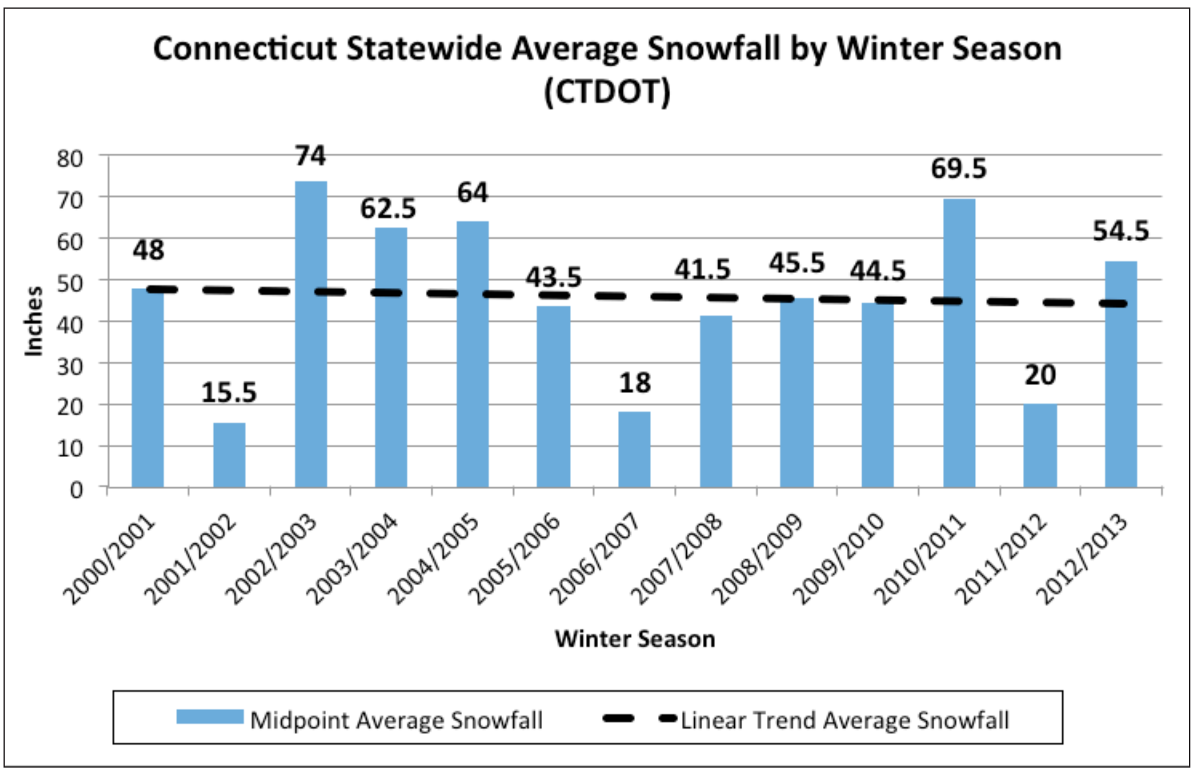


FIGURE 8.4. CONNECTICUT STATEWIDE AVERAGE SEASONAL SNOWFALL
(SOURCE: REFERENCE [4])

Figure 8.5 shows a graph with the average snowfall of Figure 8.4 superimposed on the graph of crashes with surface conditions of snow, slush or ice. A distinct relationship between the snowfall and crashes can be seen in Figure 8.5. It is visually apparent that a relationship exists between winter crashes involving injuries identified as occurring with surface conditions of snow, slush or ice and average overall snowfall. Ice is not directly accounted for in this analysis, even though the ice crashes are included in the graph. Unfortunately, it is beyond the scope of the project to identify the surface conditions with ice crashes and the weather that would correspond to those specific conditions.

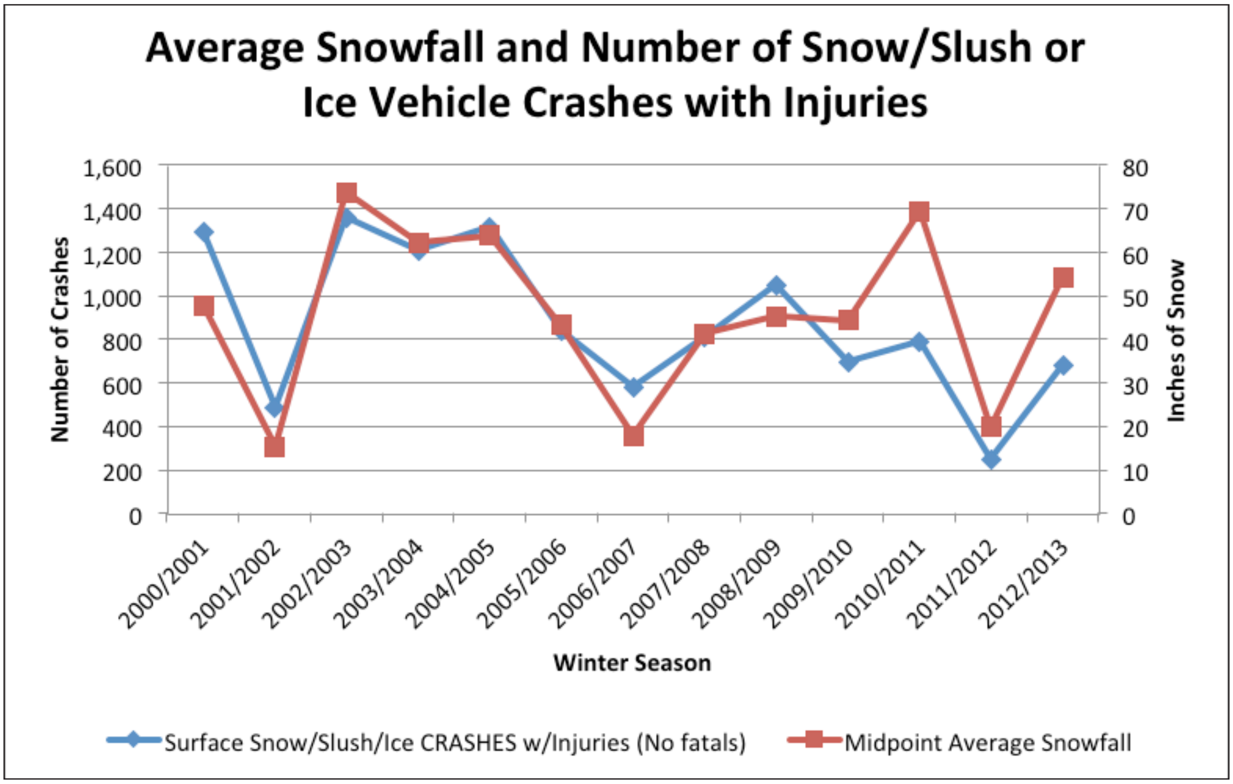


FIGURE 8.5. AVERAGE SNOWFALL (CTDOT) AND SURFACE SNOW, SLUSH OR ICE CRASHES WITH INJURIES

8.3 SUMMARY OF VEHICLE CRASH DATA ANALYSES PERFORMED

The analyses of motor vehicle crashes conducted in this study address several factors that could influence winter weather highway crashes. These factors include the following:

1. CTDOT's anti-icing winter maintenance policy
2. Winter season variations using statewide average snowfall
3. Vehicle technology changes that reduce crashes during winter weather events

The analyses performed found that crashes occurring on state-maintained highways during the winter season with pavement surfaces that were snow, slush or ice covered are less on average for the period when anti-icing was used compared to the period when sand and salt (ratio of 7:2) was in use. This finding reflects the assumption that during both of these time periods CTDOT's winter maintenance goals were to have state roads returned to safe, useable conditions as soon as practical. It is also noted that CTDOT's winter practices, as identified in the CTDOT report on its practices, have evolved over this 14-year period, along with motorists' increased expectations about maintaining mobility.

While vehicle improvements have contributed to fewer injury crashes overall, the reduction of injury crashes is greater during periods when snow, slush or ice conditions exist on roadways. Based on the available data, it is difficult to differentiate the effects of vehicle technology from winter maintenance techniques on reducing crashes, specifically when the road surface is compromised from snow, slush or ice.

8.4 ECONOMIC AND SOCIETAL IMPACTS OF IMPAIRED MOBILITY FROM WINTER WEATHER

8.4.1 Winter Weather Delays

An FHWA report, "Weather Delay Costs to Trucking" [147] prepared by Cambridge Systematics, Inc. estimated the impact of adverse weather on US roadway freight operations. The report found that the estimated cost of weather-related delay (not just winter weather) to the freight industry was 1.6% ($8.659 billion) of the total estimated freight market. The annual cost of truck delays in Connecticut due to weather events was $53.258 million, with approximately 4.4% of travel hours impacted by weather events in Connecticut, compared to a national average of 4.6%. (Note: This study did not address crash reduction benefits or the costs of crashes).[147]

Other studies cited in the above-referenced FHWA report found that

> *snow reduces traffic speed, traffic volume, and network capacity depending on the intensity of the snowfall. On average light snow, reduces speed 3 percent to 12 percent or 3 km/h to 10 km/h. Heavy snow, … reduces speed 10 percent to 40 percent or 10 km/h to 50 km/h depending on snowfall intensity, wind speed, and pavement condition, e.g., wet and slushy, compacted snow, and ice and snow. Capacity is reduced 3 percent to 20 percent with light snow and 20 percent to 30 percent with heavy snow; and traffic volume decreases 7 percent to 80 percent depending on the category of the weather event as well as visibility and wind speed* .[147]
>
> *Travel time on, the other hand, is expected to increase with snowfall. Tu, et al. (2007) estimated that there is an increase of 20 percent in travel time and Chin, et al. (2004) found that on average there is a delay of 0.2 h/driver when it snows. (*[147] *p 5).*

This reduction in traffic speed, volume and network capacity can have a significant impact on economic activity within Connecticut. The specific economic impacts during winter weather events, however, are not easy to estimate as it is difficult to measure the traffic volume reductions experienced on the entire road network over a short time period, such as during a winter weather event. However, it is probable that the user delays and increased number of people choosing to stay home for the day has a significant impact on the economy.

8.4.2 Injury Crash Costs

This chapter has analyzed winter weather vehicle crashes in Connecticut involving injuries. Many of these crashes probably incurred costs including emergency response and medical services, traffic delays due to resulting congestion, vehicle towing and repairs, post-crash cleanup of the roadway, and work productivity losses, among others.

A 2014 report of the NHTSA's National Center for Statistics and Analysis [148] found the following regarding all motor vehicle crashes in the United States (including winter crashes)

> *In 2010, there were 32,999 people killed, 3.9 million … injured, and 24 million vehicles … damaged in motor vehicle crashes in the United States. The economic costs of these crashes totaled $242 billion." "…This [$242 billion] represents the equivalent of nearly $784 for each of the 308.7 million people living in the United States, and 1.6 percent of the $14.96 trillion real U.S. Gross Domestic Product for 2010. When quality of life valuations are considered, the total value of societal harm from motor vehicle crashes in 2010 was $836 billion.*

The NHTSA report also found:

> *Public revenues paid for roughly 7 percent of all motor vehicle crash costs, costing tax payers $18 billion in 2010, the equivalent of over $156 in added taxes for every household in the United States.*[148]

The report also provided information on "nonfatal injury unit costs." According to NHTSA, police in almost every state use "KABCO" to classify victims from crashes: *"where K–killed, A–incapacitating injury, B–non-incapacitating injury, C–possible injury, or O–no apparent injury."* In a table of KABCO Nonfatal Injury Costs, NHTSA divided the injury cost into components for Medical, EMS, Market, Household, Insurance, Workplace, Legal, Congestion, Property Damage and Quality-Adjusted Life-Years (QALYs).

> *A QALY is a health outcome measure that assigns a value of 1 to a year of perfect health and a value of 0 to death (Gold, Stegel, Russel & Weinstein, 1996). QALY loss is determined by the duration and severity of the health problem, with a full year of QALY loss being equivalent to the loss of a full year of life in perfect health.*[148]

To estimate the cost of Connecticut winter season crash injuries, each of Connecticut's winter season crashes with injuries (when pavement surface was snow/slush/ice covered) were arbitrarily assigned a single victim sustaining non-incapacitating injuries. According to Table D-1 from [148] the cost of a non-incapacitating (B-type) injury is $276,010 per crash. Using this information, the cost savings resulting from a reduction in crashes after implementation of anti-icing policies can be roughly estimated. The difference in the number of crashes with injuries on surface conditions of snow/slush or ice between the deicing strategy years and the anti-icing strategy years was a reduction of 2,449 crashes as shown in Table 8.2. This number of crashes multiplied by the NHTSA cost of $276,010 per non-incapacitating injury equals a cost savings of approximately $675.9 million.

Table 8.2. Difference in Total Number of Crashes with Injuries when Road Surface Contained Snow, Slush or Ice for CTDOT's Deicing Years and Anti-Icing Years

Winter Season Months *(November, December, January, February, March, April)*	**A** *Deicing Years* (1999/2000 through 2005/2006)	**B** *Anti-icing Years* (2006/2007 through 2012/2013)	**A-B**
	Total number of snow, slush or ice crashes for 7 seasons (Sand and Salt Years)	Total number of snow, slush or ice crashes for 7 seasons (Salt Only Years)	Difference in total number of Snow, Slush or Ice Crashes from Deicing to Anti-Icing Years
Crashes with injuries when road surface contained snow/slush or ice	7,324	4,875	2,449

These cost estimates are for non-incapacitating (B-type) injuries only. According to NHTSA, each critically injured (A-type) survivor (using the MAIS 5 scale, not KABCO) costs an average of $1.0 million. The Maximum Abbreviated Injury Scale (MAIS) is an anatomically based, consensus-derived global severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale (1=minor and 6=maximal). The AIS (See http://www.aaam.org/about-ais.html for further information) was developed by the Association for the Advancement of Automotive Medicine.[148] Medical costs and lost productivity accounts for 82% of the cost for this most serious level of non-fatal injury. Therefore, for the example calculation above, in Connecticut, it would take approximately 676 crashes with incapacitating (A-type) injuries to occur to reach the ~ $675.9 million amount estimated above.[148]

8.4.3 Adverse Economic Effects of Winter Weather Events

Winter weather events have a general overall negative impact on the economy. However, this effect varies depending upon which sectors (retail, business, transportation services and other areas) are included in the analysis. Some economic analyses indicate that people would buy the same quantities of certain products such as clothing and groceries regardless of the weather. These types of purchases will just occur over a different timeframe than if no interruption as a result of weather events had occurred. Therefore, some retailers would be temporarily, not permanently, impacted. According to a study for the American Highway Users Alliance, other retailers such as gasoline stations and general merchandise would suffer permanent losses.[149]

A report on the American City and County website [150] noted that an analysis made by George Mason University's Center for Regional Analysis of Washington DC's record-breaking snowstorm in January 1996, found that during that single January month,

> *sales of nondurable goods fell $152 million and rebounded by only $85 million the next*

> *month. Yet durable goods, such as refrigerators and cars, dropped by $42 million in January but increased by $177 million in February, compensating for January losses.*[150]

The greatest impacts to society might actually be personal, due to inconvenience and uncertainty factors. Lack of mobility resulting from impassable or closed highways can affect virtually everyone who is not in the business of essential operations (snow plowing, transit, health services, police, etc.). This leads to cancelled family events, inability to travel to a job, school cancellations, and a psychological and perhaps actual danger of temporarily being trapped in your home without access or egress. These impacts may lead to increased stress and psychological issues, and may for some lead to permanent monetary loss.

The American Highway Users Alliance commissioned a study, "The Economic Costs of Disruption from a Snowstorm" (2009) [149] that was prepared by IHS Global Insight on the effects of winter snowstorms. The study provided three conclusions about a major snowstorm for areas of the country with significant snow, which includes New England.

> *1) Among all economic classes, snow-related shutdowns harm hourly workers the worst, accounting for almost two-thirds of direct economic losses. 2) The indirect economic impacts of snow-related shutdowns, including loss of retail sales tax revenues, roughly double the initial economic impact. 3) The economic impact of snow-related closures far exceeds the cost of timely snow removal. Although states and localities may be hesitant to expend significant upfront resources in the short-term, the long-term payoff more than justifies the expense.*[149]

Table 8.3 shows estimates from the American Highway Users Alliance study for the total costs incurred in specific states during a hypothetical one-day shutdown from a severe snowstorm. Although information is not provided for Connecticut, the study indicates that the cost of a one-day total shutdown in Massachusetts could have a total negative economic impact of $265 million. Estimates for Massachusetts and six other Mid-Atlantic and Northeast states are shown in Table 8.3. This economic impact includes an estimated sum of direct economic losses for lost wages, lost tax revenue, and reductions in retail trade, as well as indirect costs to the economy when lost wages are not spent in the community, resulting in lost sales. More recently, IHS Global Insight estimated that Massachusetts lost one billion dollars in wages and profits due to the extreme winter weather during 2014-2015.[151]

TABLE 8.3. ECONOMIC IMPACT OF A ONE-DAY SHUTDOWN
DUE TO A SNOWSTORM IN SELECTED STATES

State	Direct Negative Economic Impact ($ millions)	Total Negative Economic Impact ($ millions)
New York	$ 322.4	$ 700
Pennsylvania	$ 167.3	$ 370
Ohio	$ 139.5	$ 300
New Jersey	$ 132.6	$ 289
Massachusetts	$ 119.4	$ 265
Virginia	$ 120.3	$ 260
Maryland	$ 84.2	$ 184

Source: "The Economic Costs of Disruption from a Snowstorm," prepared for the American Highway Users Alliance by IHS Global Insight (2009) [149]

Money spent to keep highways open and safely navigable during winter weather events has far- reaching, but difficult to quantify, positive influence on the state's overall economy and on individuals' lives and well-being. Also, given that every highway fatality is estimated by NHTSA to result in an average discounted lifetime cost of $1.4 million, the utilization of state-of-the-art methodologies and continuous improvement for winter maintenance that can result in reduced highway fatalities, injuries and property damage, should be of high interest.

9.0 SUMMARY OF FINDINGS

Chloride-based deicing chemicals are the most common deicers used in the United States to manage the effects of winter weather on the public's mobility because of their availability, cost, effectiveness, and ease of use and storage. While it is difficult to identify which chloride causes the most corrosion since the results of laboratory tests and field tests do not necessarily agree, it is important to note that all of the chloride-based deicing chemicals accelerate corrosion. While alternative deicing chemicals, such as potassium acetate, sodium formate, propylene glycol and others, do exist, they also have issues such as environmental impacts and high costs that limit their ability to be used on a widespread basis.

Since all known deicing chemicals have some type of negative issue associated with them, such as limited availability, high cost, or potential environmental impact, chloride-based deicing chemicals will likely continue to be the primary deicing chemical used for the foreseeable future due to lower cost, abundant availability, and effectiveness. Therefore, it is important that all stakeholders involved in highway maintenance operations as well as the users of the roadways understand that everyone has a shared responsibility regarding the effects of the deicing chemicals being used.

- Transportation agencies should participate with groups such as Clear Roads, American Association of State Highway and Transportation Officials (AASHTO), National Cooperative Highway Research Program (NCHRP), the Connecticut Technology Transfer Center at UConn, the Connecticut Association of Street and Highway Officials, Inc. (CASHO) and Transportation Research Board (TRB) to remain current on the state-of-the-art practices associated with winter highway maintenance. In addition, transportation agencies need to annually review their practices to ensure that they are using an adequate amount of deicing chemicals to maintain the safety of the motoring public while at the same time balancing the impacts on the environment, vehicles and infrastructure.
- The general public shares responsibility in the process as well. Vehicle owners must understand the need to protect and periodically wash their vehicles throughout the winter to minimize the effects of corrosion by removing as much of the deicing chemicals as possible. In addition, the public needs to understand that after a winter weather event, road crews need time to return the roadways to a safe condition.
- The trucking industry also shares in this responsibility by encouraging truck and trailer manufacturers to use effective corrosion resistant practices, materials and technologies in the equipment they produce. In addition, the trucking industry needs to implement vehicle maintenance best practices such as periodic washing of the undercarriages and other critical locations to reduce the corrosive effects of deicing chemicals.

9.1 BEST MANAGEMENT PRACTICES

Winter Maintenance Policy: CTDOT's winter maintenance policy is "*The Department shall provide a standard of winter maintenance that provides for the motoring public reasonably safe roads during and after adverse weather conditions throughout the winter season.*" This policy is reasonable for addressing the challenges of the relative unpredictability of winter weather events, the demands of an increasingly mobile society, and the extensive level of resources required for maintaining mobility during adverse weather events. This study found that CTDOT succeeds in meeting these challenges by employing state-of-the-art practices, investing in new equipment and technology, maintaining equipment, training staff, participating in regional and national studies and providing a level of service that Connecticut motorists have come to rely upon.

Deicing Material Usage: After publication of the 2006 CASE report on winter maintenance, CTDOT transitioned from a deicing strategy to an anti-icing strategy, beginning in 2006/2007. This transition resulted in a dramatic reduction in the use of sand— a 97% decrease over the previous winter of 2005/2006, and by the winter of 2011/2012, CTDOT eliminated the use of sand. This transition has reduced the use of sand by an average of 239,000 tons per year for the past eight winter seasons — a total of approximately 1.9 million tons. Over the same time period (2006/2007 – 2011/2012 winter seasons), the annual increase in salt use compared with winter seasons of 2000/2001 – 2005/2006 was approximately 34% (uncorrected for seasonal snowfall variations). Elimination of sand with only a requisite 34% increase in salt provides a significant conservation of resources, resulting in fewer trips for reloading materials, longer application runs, higher service levels, reduced spring cleanup costs, as well as possibly less equipment needed to maintain similar service levels due to the effectiveness of the salt materials being used. The transition to primarily using sand has resulted in significant savings for CTDOT and municipalities.

From this study's survey of Connecticut municipalities, it was estimated that on average over the past five winters, CTDOT applied 153,000 tons of deicing chemicals as compared to the estimated total of 350,000 tons of total salt (sodium chloride, magnesium chloride, and calcium chloride) for Connecticut's municipalities. It is noted that of the state's total roadway network of 21,073 centerline miles (approx. 46,000 lane-miles), municipalities are responsible for 82% (17,339 centerline miles) and CTDOT is responsible for 18% (3,734 centerline miles). Also, whereas CTDOT has eliminated the use of sand, many municipalities still use sand for snow and ice control, thus increasing the total amount of material used by municipalities.

Information on private salt use for shopping centers, businesses, parking lots, and sidewalks in Connecticut is not available. However, if use of salt for these purposes is similar to estimates made by New Hampshire, CTDOT's deicer application may represent only 9% of the total chloride application per season statewide. These findings indicate that winter maintenance, especially the appropriate use of deicing chemicals, is a responsibility that must be shared between state, municipal and private caretakers of infrastructure.

On average over the past five seasons (2009/2010 – 2013/2014) CTDOT applied approximately 14.1 tons of sodium chloride (solid and liquid solution converted to solid) and 0.14 tons of magnesium chloride and/or calcium chloride per lane-mile (equivalent to 87 gallons of liquid magnesium and calcium chloride solutions per lane-mile) on state-maintained roads each year. In comparison with seven surveyed northeastern states, where average annual total tons of chlorides applied range from 12.5 to 31.1 tons per lane-mile, CTDOT's 14.2 total chloride tons per lane-mile ranks on the low end for salt application — only MaineDOT and VTrans had lower application rates for total chlorides per lane-mile. However, because CTDOT proactively pre-wets nearly all solid sodium chloride so as to keep it from bouncing off of the road, as well as for quick melting activation, the 87 gallons per lane-mile per season of applied liquid magnesium chloride solution (and liquid calcium chloride solution) places Connecticut on the higher end of these liquid treatment applications relative to surrounding states, just below the usage on a per lane-mile basis for New Jersey DOT (NJDOT). Some of the surveyed states use different blends of liquid and solid chemicals that make comparison between states somewhat difficult. In addition, the climate between and within each of the states can vary significantly. The overall level of service provided in each state also varies, necessitating variations in winter maintenance procedures.

Level of Service: The CTDOT report on snow and ice control operations (Appendix C) notes CTDOT has three highway classifications that help prescribe road treatments for winter maintenance. Other state DOTs use the term "level of service" to define winter maintenance operations. CTDOT identifies the three classes as limited access highways, primary routes, and secondary/miscellaneous routes. The major differences between the level of winter maintenance for each of these classes involve cycle times between treatments, the number of plows used per pass, amount of allowable snow depth accumulation, and the amount of time to have lanes cleared after conclusion of a weather event. The quantity of chemicals applied by a CTDOT maintenance vehicle per pass typically does not vary. It is usually set at 200 lbs. per lane-mile of solid sodium chloride that is pre-wetted with one gallon of magnesium chloride solution (30% magnesium chloride, 70% water by weight) per lane-mile.[8]

Recordkeeping: Accurate recordkeeping is paramount to optimizing the use of winter maintenance chemicals. CTDOT indicates that they keep detailed records of material usage for each winter weather event by maintenance section, crew, and for specific types of roadways. Data gathered from this study's survey of the type of materials and usage by municipalities indicate the potential for towns to be using greater amounts of magnesium chloride per ton of solid deicer than CTDOT. However, since several of the towns responding to the survey only provided estimates of their sand and salt use, additional data is needed to confirm this finding.

Regional Cooperation: CTDOT reports maintaining contact with surrounding states during actual and pending winter weather events. Information sharing is important for timing of staff and equipment deployment. Several towns share the purchase of treated road salt through arrangements with the Capitol Region Council of Governments (CRCOG). This likely provides a lower price for procurement due to greater bulk quantities being purchased. These examples of local and regional cooperation are important, particularly in the Northeast, which as a region has some of the most consistently severe winter weather in the country.

Safety: CTDOT's current anti-icing strategy leads to less snow and/or ice bonding to the road surface and easy removal of snow by plowing. In addition, the chemicals applied before or at the early stage of a winter weather event make ice formation below the snow layer less likely. The reduction in ice formation provides more traction (less slippery road conditions), and in theory leads to fewer vehicle crashes. The causes of vehicle crashes are many and diverse. An analysis performed in this study of vehicle crashes involving injuries showed that fewer crashes have occurred, particularly in the most recent anti-icing winter seasons compared to the deicing years prior to 2006/2007. Yet, it is difficult to document that anti-icing strategies result in fewer vehicle crashes.

It was shown in a plot of all vehicle crashes involving injuries that occurred in calendar years 2000 – 2013 (not just winter periods) that there was a steady decline in annual vehicle crashes in Connecticut on state-maintained roads nearly every year for 14 years (Figure 8.1). Much of this decline is likely the result of improved vehicle safety technology (e.g., anti-lock brakes, air bag restraints, tire tread design, stability control, traction control, all-wheel drive), as well as possibly increased seat belt usage, better law enforcement, more driver education and safety awareness, and an increase over time of the number of vehicles on the road with safety technology.

A second plot of vehicle crashes that occurred during the winter seasons (November 1 – April 30) involving personal injuries also showed a significant decline over time, but with a further step downward after implementation of anti-icing strategies (Figure 8.2). A third plot was developed for winter season crashes with injuries that occurred when the road surface was reported as snow, slush or ice covered (Figure 8.3). This graph indicated a significant year-to-year variability of crashes with injuries. What is noted from this plot, however, is that the number of crashes involving injuries with the pavement surface containing snow, slush or ice is trending downward after the implementation of anti-icing strategy; in contrast, during the deicing years of 1999/2000 – 2005/2006, the plot trended upward (increasing). The average number of winter season crashes with injuries for the seven years since anti-icing was implemented is 33.5% lower than for the seven prior years. Finally, a plot of the average snowfall amount superimposed on average crashes with injuries when the surface was snow, slush or ice covered indicates that a definite relationship exists between average seasonal snowfall and number of vehicle crashes (Figure 8.5). It is noteworthy that the most recent four winter seasons since 2008/2009 show a greater variance between snowfall amounts and vehicle crashes, with fewer crashes relative to snowfall amount. However, the data used for this analysis do not include freezing rain events. Without this information, the relationship of weather to crashes is not completely defined in this analysis.

Therefore, even though a significant decline in winter weather vehicle crashes with injuries was demonstrated, the extent to which this decline was a result of anti-icing strategies cannot be definitively quantified. Much of the decline may be attributable to vehicle safety technology, but it is quite likely that a portion of this decline is also a result of implementation of anti-icing policies.

Mobility: During winter weather events, precipitation causes a reduction in traffic volumes, traffic speeds and network capacity, and typically increases travel time. Weather delays for travel cause significant temporary disruptions to commerce. The FHWA estimates that the annual cost of truck delays in Connecticut due to year-round weather events is approximately $53.3 million. FHWA also reported that approximately 4.4% of travel hours in Connecticut over the course of a year are adversely impacted by weather events. This same report notes that in general the freight industry thoughout the United States has an added annual cost of $8.7 billion (or 1.6%) due to weather-related delays. These statistics indicate that efficient and timely removal of snow and ice from roadways is an important factor to keeping delays and associated costs minimized in Connecticut.

Vehicle Crash Costs: Vehicle crashes contribute significant negative costs to society. Each major crash can involve emergency response, medical services, congestion and associated delays, towing costs, repair costs, potential introduction of toxic chemicals related to crashes into the environment, auto insurance rate increases, post-crash cleanup, and work productivity losses, and other factors. NHTSA has reported in [148] that all motor vehicle crashes in the United States during 2010 resulted in 32,999 deaths, 3.9 million injuries and 24 million damaged vehicles. The economic costs of these crashes in 2010 represented $242 billion, which was 1.6% of the US gross domestic product (GDP).

As an illustrative example, a rough estimate of the cost to society of Connecticut victims sustaining non-incapacitating injuries during winter weather season crashes was calculated. The crashes used for the analysis occurred when the road surface was identified as being snow, slush or ice covered at the time of crash. A reduction of 2,449 crashes was counted under these pavement conditions during the anti-icing period from 2006/2007- 2013/2014 compared with the deicing period from 1999/2000 – 2005/2006. For purposes of this example, each crash was arbitrarily assigned one non-incapacitating injury. NHTSA estimated that the cost of this type of injury was $276,010 per crash in 2010. The total cost savings due to the reduction of 2,449 crashes is therefore calculated to be $675.9 million.

Adverse Economic Effects of Winter Weather Events: Researchers have quantified that winter weather events affecting mobility can have negative effects on an economy. These effects vary depending upon which sectors (retail, business, transportation services and other areas) are included in the analysis. Some retailers may be temporarily, if not permanently, impacted by severe winter weather events. According to a study for the American Highway Users Alliance, other retailers such as gasoline stations and general merchandise would suffer permanent losses.[149]

Lack of mobility resulting from impassable or closed highways affects virtually everyone who is not involved with essential operations (snow plowing, transit, health services, police, etc.). This leads to inability to travel to a job, school cancellations, a psychological and perhaps actual danger of temporarily being trapped in your home without access or egress, and cancelled family events. These impacts may lead to increased stress and psychological issues, and may for some lead to permanent monetary loss, particularly for hourly wage workers.

The American Highway Users Alliance study [149] estimated the total costs incurred in specific states during a hypothetical one-day shutdown from a severe snowstorm (Table 8.3). Although information is not provided for Connecticut, the study indicates that the cost of a one-day total shutdown in Massachusetts could have a total negative economic impact of $265 million. This economic impact includes an estimated sum of direct economic losses for lost wages, lost tax revenue, and reductions in retail trade, as well as indirect costs to the economy where lost wages are not spent in the community, and lost sales occur as a result. More recently, IHS Global Insight estimated that Massachusetts lost one billion dollars in wages and profits due to the extreme winter weather during 2014-2015.[151]

This indicates that the effectiveness of Connecticut's response to winter weather events can have a significant positive or negative effect on Connecticut's economy.

9.2 DEICING MATERIALS

Chemicals: Chemicals used for melting snow and ice reviewed for this study were primarily those that are commonly in use in Canada and United States, and include both inorganic and organic compounds. Sodium chloride, calcium chloride and magnesium chloride are the inorganic chemicals used for deicing. The organic deicing chemicals reviewed include calcium magnesium acetate (CMA), potassium acetate, sodium acetate, sodium formate, potassium formate, urea, propylene glycol and agricultural-based by-products. Also, at least 250 proprietary deicer products were identified. Most of the proprietary products contain a combination of the same chemical deicers listed above, plus corrosion inhibitors, anti-caking additives, and colorants. Approximately 100 proprietary products are listed in Appendix F.

Advantages and disadvantages of the chemicals reviewed are summarized in Appendix E. The effectiveness of chemicals used for deicing is primarily based on their ability to lower the freezing point of water. One major disadvantage of using organic deicers is that during decomposition, the microbes degrading the chemicals require a great deal of oxygen—otherwise known as Biochemical Oxygen Demand (BOD). BOD can rapidly deplete the dissolved oxygen in bodies of water, thereby negatively impacting aquatic wildlife.

The three chlorides that were found to be the most extensively used deicers, were so in part due to availability of quantities required, reasonable price, proven effectiveness and ease of storage and use. The alternatives were all either too expensive, only available in limited quantities, or have had only limited use in the United States—and as mentioned, from an environmental perspective, BOD is a concern.

Abrasives: Abrasives are defined as *sand or grit-sized aggregates* (e.g., sieved bank run gravel, incinerator ash or mining slag "clinker," and cinders). The primary function of abrasives is to provide temporary traction on snow and ice surfaces. However, most abrasives are readily removed from the roadway with the passage of traffic, deeming them ineffective shortly after application. It is estimated that more than 50% of abrasives that are applied on roadways are not recovered. For this reason, and others, such as adverse effects on air quality and added costs for sweeping, removal and disposal, there has been a continuing decline in the use of abrasives throughout the United States. CTDOT discontinued using its standard sand and salt mix (7:2 ratio) in 2006, around the time of the previous CASE study.[1] At that time, it was apparent that many other states were transitioning away from the use of abrasives due primarily to their lack of effectiveness and the cost of cleanup (removal).

This study's survey of Connecticut's municipalities showed that abrasives are still in use, and for emergency situations by CTDOT. While CTDOT has transitioned to minimal use of sand, 31 (67%) of the 46 municipalities that responded to the survey used sand in regular winter highway maintenance operations in at least one of the previous five years, and applied approximately 7.8 tons of sand per lane-mile in their respective towns during the winter of 2013/2014 (Figure 2.2).

9.3 CORROSION

Joseph Payer, Chief Scientist of the National Corrosion Center, University of Akron, noted in a CASE meeting on October 20, 2014 that corrosion prevention strategies for highway infrastructure and vehicles are needed. These needs are both non-technical (increased awareness, elimination of a misconception that nothing can be done, a need for changed policies, regulations, standards and management practices, and improved education and training) and technical (implementation of advanced design practices, a need to advance life prediction and performance assessment methods, as well as research development and the implementation of corrosion technologies).[89]

Effects of Deicers: Reliance upon the results of laboratory studies and/or field studies independently may not provide a complete picture of the effects of deicing chemicals on infrastructure and vehicles. For instance, due to their design for accelerated results, laboratory tests may exaggerate the effects of chlorides or potassium acetate on concrete. On the other hand, applying deicing chemicals in the field may require extended observation periods of several years in order to detect any negative effects from the chemical deicers.

Effects of Chlorides - Infrastructure Field Studies: Many laboratory studies have been completed over the past 25 years on the effects of chlorides on concrete and steel (Chapter 6). However, in the few cases where field studies were performed in an attempt to verify the results of laboratory studies, results did not indicate or show definitive evidence that field conditions matched lab test conditions. Generally speaking, due to dilution, the levels of chlorides and other chemicals applied in the field during winter maintenance activities are several magnitudes lower per application than for many of the lab tests. Lab tests are usually performed over a few months, or up to three years, using accelerated test methods. The highway infrastructure has been exposed to hundreds or thousands of doses of deicers over as many as 60 years, in the case of sodium chloride, or possibly 25 years in a few northern and western states for magnesium chloride or calcium chloride. CTDOT has used only relatively small amounts of calcium chloride solution and magnesium chloride solution as compared to sodium chloride (solid and in solution) for the past nine winter seasons.

Damage found in PCC in the field that typically might be attributed to corrosion include fine surface cracks (also known as map cracking in concrete), surface scaling due to loss of mortar, popouts, durability cracking near concrete joints and edges of concrete pavement, spalls (cracking, chipping, breaking), rust, and rust stains. Some normal corrosion occurs regularly from combinations of wear, water, air and vibratory damage, regardless of exposure to chlorides. However, chlorides can contribute accelerated damage to PCC. Additional field studies are needed before an assessment of the true effects of chlorides on concrete infrastructure can be made.

The effects of chloride deicers on asphalt pavement, which is the major riding surface on the majority of Connecticut roadways, is considered negligible. The asphalt binder and aggregates used in asphalt pavements do not react chemically with chlorides. Asphalt pavements, being more flexible than PCC, generally can withstand the physical expansion and contraction caused by freeze/thaw cycles at the surface.

Effects of Chlorides: Infrastructure Lab Studies: Literature from approximately a dozen studies performed between 1995 and 2012 showed that the laboratory studies primarily examined the corrosive effects of sodium chloride, calcium chloride, magnesium chloride, and/or calcium magnesium acetate on common transportation infrastructure materials, including concrete and/or steel and/or steel-reinforced concrete. Common physical effects of chloride deicers in the laboratory are primarily damage from freeze-thaw cycling. Chemical reactive effects include reactions with cement paste, reactive aggregates, and corrosion of steel.

All but one of the studies reviewed found that magnesium chloride and calcium chloride cause more damage to PCC than sodium chloride. Most found magnesium chloride to be more damaging than calcium chloride due to the creation of magnesium silicate hydrate and brucite crystals. Both of these weaken and deteriorate the surface of the concrete. Chemical reactions between the concrete and magnesium chloride/calcium chloride typically increase the porosity of the concrete. As a result, magnesium chloride and calcium chloride are indicated to cause more damage to reinforcement steel within concrete than sodium chloride.

Condition of Infrastructure: It is difficult to assign a specific level of damage that chemical deicers play in the corrosion of structures, such as highway bridges. However, CTDOT's Bridge Safety and Evaluation Unit suggests that the majority of deficient bridges have various levels of corrosion as the most common issue, such as to the rebar in the deck, substructure, and steel beams/girders. Beyond corrosion, there are other factors such as fatigue, scour from waterways, and poor material/construction quality that all play a part in some of the structural deficiency ratings.

CTDOT data indicate that, in 2014, 7.3% of CTDOT-maintained bridges were rated as structurally deficient. The FHWA, who collects condition of infrastructure from all states, indicates (Table 6.3) that in December 2014, that 9.0% of CTDOT-inspected Connecticut bridges (which include other bridges besides those maintained by CTDOT) were structurally deficient. This level should be considered in the context of Connecticut's neighboring states that had structurally deficient bridges ranging from 7.5% to 22.7%. However, the cost to upgrade or replace structurally deficient bridges is very high. According to the *ASCE 2013 Report Card for America's Infrastructure*, [119] in the United States, a total of $76 billion—typically using both federal and state funding —would be needed to repair just those bridges rated deficient.

Corrosion Inhibitors: There is a public misconception, possibly as a result of media information and marketing by vendors, that corrosion inhibitors used with deicers will protect motor vehicles and the bridges and pavements on which they travel. In this study's literature review, no information was found that shows corrosion inhibitors in deicing chemicals are beneficial for protecting vehicles or infrastructure; the exception to this was for trucks that are used to apply the deicing chemicals. It is difficult to find specific information from any of the manufacturers of deicer products that defines materials that corrosion inhibitors are intended to protect. Most proprietary corrosion inhibitor manufacturers claim that their products meet the Pacific Northwest Snowfighters Association (PNS) requirement that a deicer be 70% less corrosive on specified steel coupons than rock salt. Also, PNS has additional requirements for a product to be listed on their approval product list.

Although it would seem intuitively obvious that salts in direct contact with deicer spreading equipment would be problematic with respect to corrosion, and that inhibitors may be beneficial, the same is not true for roadways and bridges, where the chemicals become greatly diluted in a relatively short period of time during winter weather events. The inhibitors and additives that are found in many, if not most, proprietary deicers are difficult for the consumer to identify. The companies that mix and distribute the products tend to protect their right of trade secrets on ingredients. However, considering the extent of coverage of deicers that are applied to over 20,000 lane-miles of roads in Connecticut and untallied acres of parking lots, from dozens of applications a year, it would seem beneficial that the content of materials be defined, and known, by users of the products.

Since many available corrosion inhibitors are biodegradable, there is some concern about increased BOD induced in adjacent streams for certain time periods during the season after several applications of deicers may have accumulated. The actual environmental impact is not completely known. Other corrosion inhibitors in use may not be biodegradable, and their chemical makeup could also come into question with respect to impacts on surrounding areas adjacent to roadways. CTDOT has decided not to use corrosion inhibitors with deicers at this time. More research is needed to identify the effectiveness of inhibitors for corrosion prevention, as well as environmental effects.

Bridge Rinsing: A study conducted on behalf of the Washington State DOT that included a survey of states found a majority of states responding to the survey either "wash" bridges frequently or they don't wash at all. Of the 34 state DOTs who responded to the survey, 17 never wash bridge decks, and approximately 10 never clean expansion joints or bearings. None of the transportation agencies indicated that they had performed studies on the cleaning of decks, bearings or expansion joints to determine the impact on component life. States near Connecticut that indicate they clean or wash bridges include: Maine, New Hampshire, Pennsylvania, New York and Vermont; with Maine and Pennsylvania indicating that they wash decks every year. CTDOT conducted a bridge rinsing pilot program that rinsed 25 bridges that did not cross waterways. The program was concluded in 2012. A more permanent and longer term rinsing program is under consideration with planning being done in cooperation with DEEP.

Protection of Infrastructure: Many practices can be implemented to protect structures from the effects of deicing chemicals:

- For steel bridges, these actions include
  - maintaining proper coatings on exposed steel members within the bridge;
  - ensuring that the bridge joints are in good condition and minimize water infiltration; and
  - cleaning the structures periodically to remove chlorides, as well as other debris that may hold moisture and allow corrosion to occur.
- For concrete structures, these actions include
  - using polymerized concrete for the wearing surface on bridge decks;
  - using a waterproofing membrane on the bridge decks before paving them with asphalt;
  - ensuring proper concrete cover for steel reinforcement;
  - using corrosion inhibitors within the concrete and incorporating high density/ low permeability concretes into designs to minimize chloride penetration;
  - using epoxy-coated steel, ensuring that any damage that is detected during the placement of the steel is repaired before placing the concrete; and
  - using stainless or galvanized steel for reinforcement of high volume structures.

In addition, some states have been using silanes to seal their concrete bridge decks. The Oklahoma DOT is one of a few that have studied coating bridge components with silane. Silane performance was evaluated with respect to depth of penetration, absorption, water vapor permeability, and chloride ingress. Results indicated the need to represent field conditions (particularly mix design) to the extent possible in order to predict better field performance with laboratory tests. High Molecular Weight Methacrylate (HMWM) can also be used on bridge decks to help seal small cracks that form. It is recommended that the HMWM be applied several months after construction, before any chlorides are applied to the bridge deck. HMWM can be used in conjunction with silane sealers to help slow the penetration of chlorides into the concrete. All concrete sealers need to be reapplied periodically in accordance with the manufacturer's recommendations.

Motor Vehicle Corrosion: The presence of chlorides accelerates atmospheric corrosion by increasing the conductivity of trapped moisture. The loss of integrity of brake components, undercarriage components such as frame members, and electrical components is considered to be structural and a safety issue. The staining and bubbling of paints is cosmetic, and affects primarily aesthetic appearance.

Several presentations provided to the CASE Study Committee included representatives of trucking firms, vehicle manufacturers, paint and coatings distributors, and trucking associations. Anecdotal evidence indicated that corrosion increased around 2005, about the time that many states started using magnesium chloride. Most published documents about this topic are newsletters or trade magazine articles. There does not appear to be much published (peer-reviewed) research on quantitative studies of truck or automotive corrosion.

Some of the potential solutions presented to assist in combating vehicle corrosion included

- better monitoring (visual inspections) and data collection (documentation);
- employing proper maintenance procedures;
- frequent equipment washing;
- use of more lubricants and anti-corrosive sprays on components that are most exposed to deicing chemicals (electrical sockets, pigtails, battery terminals, connections);
- vehicle material and specification changes (more aluminum, galvanizing, special paints, undercoatings);
- more interaction with equipment manufacturers;
- better warranty programs;
- improved paints and coatings;
- use of corrosion-resistant materials, dielectric grease, enclosed wiring connections;
- use of sacrificial anodes; and
- use of corrosion-inhibited products

It was reported that the life of a truck body is highly dependent upon maintenance performed. When little or no maintenance is performed, a truck trailer life may be constrained to five to seven years. With occasional but ineffectual preventive maintenance, the life may be seven to 10 years. However, proper preventive maintenance, including the repair of dents, gouges, scrapes, and hinges, and any process to stop corrosion before it migrates, should lead to a truck trailer life of 20 years. Other corrosion preventative actions include

- more widespread use of stainless steel and galvanizing;
- better coatings and application methods;
- increased warranties on lighting systems;
- improved barriers between dissimilar metals; and
- elimination of moisture-harboring crevices in the truck bodies.

Other circumstances that occurred concurrently with CTDOT's transition to using all salt for winter highway maintenance that are likely contributors to an increase in vehicle corrosion beginning approximately around 2005 include

- the phase-out of the use of hexavalent chromium (Chrome VI);
- the elimination of cadmium in electronics; and
- the elimination of incorporation of lead in certain metals for corrosion resistance.

Vehicle Washing: Removal of salts from vehicles is a common practice cited for preventing vehicle corrosion. In fact, a NHTSA safety advisory (April 9, 2015) [133] recommended washing the undercarriage of all vehicles regularly to prevent corrosion of critical components of brakes and suspension, particularly for model years 2007 and earlier, and in the 21 states (including Connecticut) where the most winter deicers are used.

Commercial car washes in Connecticut may use either fresh water, or recycled water that may or may not be diluted with fresh water for washing vehicles. However, it is noted that it may be better to use water that is somewhat brackish as opposed to not washing vehicles. Currently it is not possible to quantify the benefit of washing vehicles in commercial car washes since the concentration of deicing chemicals in the water being used — especially for undercarriage washes — is either not available or not disclosed by commercial car washes. An opportunity exists to strengthen the transparency and availability of information if commercial car washes voluntarily disclose to the public the content of the car wash water that is used for salt neutralizers, wax, and salt or recycled water content, among others.

9.4 ENVIRONMENTAL EFFECTS OF WINTER MAINTENANCE

The environmental impacts of chloride salts depend on the pathways and rates at which they travel through the environments adjacent to roads. Traffic-generated spray (aerosols) containing chloride salts can transport short distances, potentially impacting roadside wetlands, soils and vegetation. Surface runoff and groundwater can travel greater distances than aerosols, impacting lakes and streams. The rate at which groundwater travels and the resulting impacts of chloride salts depend on whether the aquifer is shallow or deep. The transport of chloride salts through any of these pathways depends on physical and chemical characteristics of the landscapes (soil type, vegetation density, slopes, etc.), the chloride salt (e.g., chemical form, particle size), and the weather conditions (e.g., temperature, humidity, rainfall volumes and rates).

Impact of Chlorides on Soils: In applications that are high in rock salt where sodium is the dominant cation, sodium can become the dominant exchange ions, effectively stripping the soil of several macronutrient (calcium, magnesium, potassium and ammonium) or micronutrient (copper, zinc, or manganese) cations that are required for plant growth. Researchers have also found that chloride salt applications lead to leaching of trace metals (e.g., cadmium, copper, lead, zinc, nickel) that could be toxic to organisms living in waters. Impacts on soils have been observed as far as 100 feet from the road.[57][51]

Impact of Chlorides on Groundwater: The concerns related to chloride salt applications impacting groundwater are related to human health and aesthetics. In this case, sodium is the primary concern, with the potential to lead to hypertension.[51] For the portion of the population on a sodium-restricted diet, the current EPA guidance level for sodium is a maximum of 20 mg/L. DPH has set 28 mg/L as the notification level for sodium in public drinking water. Recently, DPH recommended that private well owners notify their doctor if they are on salt-restricted diets and if the sodium level in their well water is over 100 mg/L.[60] Ultimately, elevated levels of sodium and chloride will translate into higher concentrations in surface waters as this water works through the hydrologic system.

Impact of Chlorides on Surface Water: Small streams adjacent to urban areas are the most at risk for increased sodium and particularly chloride concentrations. However, once runoff enters streams, concentrations are diluted substantially. Typical chloride concentrations in surface waters range from 0 to 25 mg/L [62] although concentrations of chloride in runoff from chloride salt application areas approaching seawater level concentrations of around 20,000 mg/L may be observed.[51]

Impact of Chlorides on Biology: Roadside vegetation exposed to chloride salts can uptake excess salts through the soil media or accumulate salt on foliage due to spray. Several studies [65][66] suggest that the most affected roadside vegetation is within 22 feet on uphill roadside slopes to 53 feet for downhill roadside slopes. Aquatic life can be strongly impacted as well depending upon chloride salt concentration, through two primary mechanisms, water circulation and osmotic regulation. Changes in an organism's ability to control osmotic regulation can result in toxicity. Lethal toxicity is a function of exposure, including both concentration and duration. EPA has set aquatic life acute and chronic toxicity levels for chloride of 860 mg/L and 230 mg/L with durations of one hour and four days, respectively. [52]

Research on the impacts to small invertebrate animals, such as insect larvae, living in water bodies receiving roadway runoff, is mixed in terms of changes in species abundance and diversity. Some researchers report observing significant decreases in species diversity downstream of road salt application areas, while others have not observed any effects.[51] For amphibians, such as the green frog, wood frog, or spotted salamander, increasing levels of salinity have resulted in negative effects on growth rates and survivorship.[69][70][51]
Effects of Organic Chemicals: Acetates, formates or other organic-based deicing products, as well as corrosion inhibitors, have potential environmental impacts related to dissolved oxygen

levels in receiving soils or waters. Organic deicing materials and corrosion inhibitors contain simple organic molecules that are readily consumed by bacteria, utilizing oxygen in the process and resulting in lower dissolved oxygen in water bodies. The secondary effect of reduced oxygen in surface waters in particular is death of aquatic organisms. There are no documented instances of low dissolved oxygen levels linked to organic deicing products or corrosion inhibitors; however, they are not currently in widespread use.

Connecticut Specific Environmental Effects: Since the early 1900s, average statewide chloride concentrations in well waters have increased by tenfold, to approximately 20 parts per million, [76] and this increase has been spatially correlated with major roadways. Within the state of Connecticut, private drinking water wells have had instances of high concentrations of sodium or chloride in their wells. Since 2014, 10 cases have been reported to the private well program at DPH [77], primarily in regards to elevated chloride concentrations. Based on additional discussion with Bill Warzecha, a supervising environmental analyst in the groundwater remediation group at DEEP, 10 cases have been reported this season (some may overlap with DPH reported cases). The most common cause of increased sodium or chloride concentrations was found to be stockpiling of salt laden snow on top of a well casing or with a shallow drinking water well.

Removal or treatment of chloride from water is difficult, costly, and impractical for large volumes; thus the only effective management strategies include reducing chloride salt application, altering the concentration through dilution with other waters, or re-routing runoff to less sensitive receiving waters.

In summary, groundwater concentrations of chloride have increased over the last several decades, with average concentrations in Connecticut increasing by tenfold over the past century. While chloride is only part of a secondary drinking water standard, meaning it does not pose a risk to human health, and sodium levels are only offered as guidance for people with low-salt diets, the instances of elevated concentrations should be monitored, with appropriate actions taken as necessary.

Currently in Connecticut, there are no impaired water bodies listed for chloride. Previous studies by USGS and DEEP on water bodies expected to receive high chloride concentrations and loads have not shown chloride levels to exceed the acute or chronic toxicity criterion.

It should also be noted that CTDOT has spent millions of dollars over the past 20 years to construct 88 state-of-the-art salt storage sheds. These salt sheds alleviate the runoff that would occur from uncovered outdoor stockpiles.

9.5 NEW TECHNOLOGIES AND PRACTICES FOR WINTER MAINTENANCE

It was found in this study that CTDOT has adopted a number of state-of-the-art technologies and best management practices for winter highway maintenance. The following equipment technologies have been tested and/or fully adopted by CTDOT. Also, many of the equipment technologies listed have the potential to aid municipalities in providing better winter highway maintenance levels of service.

- Salt slurry application trucks *(currently being evaluated by CTDOT for implementation)* create an oatmeal consistency slurry that is applied to a roadway to prevent bouncing and scattering.
- Zero velocity spreaders reduce bounce and scatter of material applied to a roadway.
- Ground speed oriented controllers adjust the amount of material being applied based on vehicle speed, resulting in cost savings through reduced material usage.
- Truck-mounted air and pavement temperature sensors provide real-time weather information in order to adjust material application rates.
- RWIS provide valuable data for winter weather event management and decision making, including air temperature, wind speed, type and rate of precipitation, surface temperature, concentration of deicer on surface, water freeze point calculation, and other useful data.
- Underbody plows are plows mounted beneath the truck between front and rear axles capable of producing downward pressure for optimal scraping.
- Multi-sectional plows are plows with smaller segments that move up and down to conform to the pavement cross section.
- GPS and automatic vehicle locator systems increase productivity and efficiency by allowing managers to view plow routes, cycle intervals, and application rate settings.
- Loader weighing systems are used to weigh materials loaded into trucks using load sensors attached to front end loaders.

The following practices have potential to assist CTDOT, as well as municipalities, reach a goal of providing winter highway maintenance operations that provide the highest level of service for the winter weather conditions at that time:

- development of a winter severity index
- development of a roadway condition index
- communication and notifications to the public via the media
- outreach, transparency, and public education
- additional training
- development and posting of winter maintenance performance measures

10.0 CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

The use of chloride-based deicers for winter highway maintenance operations is ubiquitous throughout the northeastern United States. There are many reasons that these products are widely used, including effectiveness, cost, and ease of handling and application. The primary deicing chemical used by CTDOT is solid sodium chloride with a small amount of calcium or magnesium chloride in a pre-wetting solution. Over the past five years, the amount of calcium or magnesium chloride applied represents 1% of the total chlorides applied in Connecticut and 0.3% throughout the surveyed states in the northeast region.

At the present time no products have been identified that can achieve the same level of effectiveness of chloride-based deicers. Therefore, it should be assumed that chloride-based deicers will be used as the primary deicers for winter highway maintenance for the foreseeable future.

CTDOT has been proactive in transitioning from a strategy of deicing during a winter weather event to a strategy of anti-icing, including:

- Elimination of the use of sand;
- Pretreating with sodium chloride brine solution;
- Pre-wetting of solids with a solution of calcium or magnesium chloride;
- Making plans to increase the number of Road Weather Information Stations (RWIS); and
- Experimenting and conducting pilot trials with salt slurry generators.

The year-round overall number of vehicle crashes that result in injuries to vehicle occupants on roads maintained by CTDOT has been trending downward for 14 years. This 14-year period includes the final seven years of CTDOT applying sand-salt mix and the first seven years of CTDOT transitioning to and using only salts. When the data trends were analyzed using the switchover to all salt as the dividing point, there was a distinct difference between the seven years of the sand-salt mix and the seven years of the all-salt application. The all-salt period had a distinct decrease in the trends for injury crashes occurring on snow, slush or ice-covered roads as compared to the trends during the final seven years of the sand-salt mix. While it is not possible to conclude with certainty that the switchover to all salt was responsible for this change in the data trends, it is difficult to ignore that something changed with regard to the trends in the injury crashes occurring on snow, slush or ice-covered roadways.

The use of any chloride-based deicers accelerates the corrosion of metals and concrete, which will have a negative impact on vehicles and infrastructure. There are also environmental impacts of using chloride-based deicers. The negative impacts of using chloride-based deicers must be balanced with the improved roadway safety and positive economic impacts that result from effective and prompt winter highway maintenance practices in response to winter weather events. Since this impacts almost all citizens of Connecticut in some manner, there is a need for everyone to share in taking responsibility for these impacts.

Connecticut's transportation agencies are working efficiently and economically in an effort to restore the roads to a safe and passable condition as quickly as possible during winter weather events while minimizing the amount of deicing chemicals that are being used. Vehicle owners need to understand the importance of washing their vehicles (including the undercarriage) after a winter weather event and the roads have dried. The general public needs to have realistic expectations for restoring mobility following a winter weather event. Since Connecticut is located in a part of the country where deicing chemicals are used, the owners of vehicles and infrastructure need to periodically inspect their assets and be prepared to respond when problems are identified.

Chloride-based deicers are inorganic chemicals that will not be broken down by natural processes. Therefore, the buildup of chlorides in the environment can present problems for aquatic wildlife during the winter weather season, when these chemicals are being applied, as well as throughout the entire year as the chlorides work their way through the groundwater and are slowly released into waterways. Alternative deicing chemicals tend to be organic chemicals that can present problems as they travel through the environment. The microbes that consume the organic deicers require oxygen to breakdown the deicing chemicals. This can deplete the dissolved oxygen in the groundwater and waterways. In addition, some of these organic deicing chemicals will provide nutrients for algae in waterways once they have been broken down by microbial activity. Since there is little experience with transportation agencies using organic deicers on a wide-scale basis, the long-term effects on a grand scale are not completely known. In addition, some agricultural waste products that are used, such as beet juice, are generally mixed with chloride-based deicing chemicals before they are applied. These liquid agricultural waste materials tend to be more effective at preventing water from freezing and are not as effective as chlorides at melting snow and ice.

Corrosion inhibitors and salt-neutralizing wash additives are being marketed as a method of reducing the impacts of the deicers. Many of the corrosion inhibitors intended to be applied with the deicing chemicals are organic in nature, with the intent that the organic chemicals will consume oxygen before they can react with iron to form rust. Given the dilution that occurs at the time of application, it is highly unlikely that corrosion inhibitors can have much of an effect on infrastructure and vehicles traveling through the melt water. During this study, literature supporting the effectiveness of corrosion inhibitors in laboratory testing was identified; no literature was found that documented the benefits of corrosion inhibitors when they are used in the field. There may be some benefit to using a corrosion inhibitor on the vehicles that apply deicing chemicals, which is where the concentration of the inhibitor is the highest. Without any documented benefit of using corrosion inhibitors for the motoring public, applying additional chemicals with associated environmental impacts and added cost may not be worthwhile unless the agency applying the deicing chemicals finds it will be beneficial to their fleet.

Salt-neutralizing wash additives are intended to be used for washing equipment to minimize the effects of the chloride-based deicing chemicals. The literature reviewed showed mixed results as to their effectiveness. In some cases the salt neutralizers that were used at the manufacturer's recommended concentrations actually increased the corrosion of the metals. In some cases, when the neutralizer was used at a higher concentration than that recommended by the manufacturer, the corrosion for some metals decreased. Further, based on the type of metal, the results varied, with some metals showing decreased corrosion and others increased corrosion.

One of the most difficult aspects of analyzing winter weather events and seasons is the variability that occurs from storm to storm and each winter season. Some of the variables that affect an agency's snow and ice control practices include:

- amount of precipitation
- event duration
- intensity
- day of the week
- traffic volume
- temperature (including before, during and after the event)
- wind speed
- time of the year (strength of the sun's rays)

10.2 RECOMMENDATIONS

CTDOT should continue to participate in groups such as Clear Roads, AASHTO, NCHRP and TRB to remain current on best practices for snow and ice control. Participation in these groups will enable CTDOT to be aware of emerging best management practices and to adopt those that provide improved strategies that lead toward optimizing the department's winter highway maintenance operations (i.e., maximize impact of chemicals and minimize excess use of chlorides). CTDOT should also work to ensure that successful technology and operation improvements are shared with municipalities for their consideration and implementation. CTDOT should seek assistance from organizations such as the Connecticut Technology Transfer Center at UConn and the Connecticut Association of Street and Highway Officials, Inc. (CASHO), among others, for sharing winter highway operations practices and advancements with municipal transportation agencies.

The following recommendations are provided for consideration by CTDOT and Connecticut's municipalities. Some of the suggested recommendations have already been implemented by CTDOT and some municipalities.

10.2.1 Deicing Chemicals and Application Techniques

10.2.1.1 DEICING CHEMICALS

Currently, chloride-based snow and ice control chemicals are the most effective and economical treatments readily available, and will be the most commonly used deicing chemicals for the foreseeable future.

a. CTDOT should continue to use sodium chloride as the primary deicer; it remains the most economical inorganic chemical and is an effective deicer under most conditions above 20°F. While typically temperatures in Connecticut under most winter weather conditions are above 20°F, for lower temperatures, materials application rates may be varied due to conditions.

b. CTDOT should continue to mix brine (sodium chloride in solution with water) in-house, rather than purchase mixed materials containing unspecified additives.

c. While organic chemicals (i.e., potassium acetate, sodium formate and propylene glycol, among others) can potentially be used in very specialized circumstances or unique situations for snow and ice control, availability, cost and unintended environmental consequences from the breakdown of organics may be problematic.

10.2.1.2 PRE-WETTING

Pre-wetting is an effective practice that is used to moisten salt or sand (where still in use) prior to application. It reduces the tendency of these materials to bounce off the road and activates faster melting. CTDOT should continue, when feasible, to use sodium chloride solution for pre-wetting at the beginning and end of seasons and magnesium chloride solution during the coldest months, to assist in lowering the temperature at which the solid sodium chloride is effective.

a. The chloride-based chemical selected for the pre-wetting solution ideally should be determined based on forecasted temperatures during periods within the winter season. For example, sodium chloride solution can be used for pre-wetting during the warmer months at the beginning and end of the winter season, with magnesium chloride solution used generally mid-December through the end of February.

b. If uninhibited liquid calcium chloride solution is available and cost-effective, it should be considered for the pre-wetting solution in lieu of liquid magnesium chloride solution; while all chlorides are corrosive to metals, calcium ions are less damaging to Portland cement concrete than magnesium ions.

10.2.1.3. PRETREATING

CTDOT should continue the use of sodium chloride solution for pre-treatment of bridges and known problem areas. Pretreating bridge decks, hills and shaded, north-facing roadways is an effective strategy for enhancing safety and reducing callout of maintenance personnel after hours, resulting in a reduction of overtime pay.

a. CTDOT's strategy of using sodium chloride solution as pre-treatment appears to be successful. Switching to a calcium chloride or magnesium chloride-based pre-treatment does not appear to be warranted in Connecticut's climate.

b. CTDOT should promote the use of sodium chloride solution pre-treatment in larger municipalities for problematic areas.

c. CTDOT should promote the use of solid proprietary salt or pre-wetted salt for pretreating in smaller municipalities.

10.2.1.4. ANTI-ICING STRATEGY

CTDOT should continue with the anti-icing strategy that was initiated during the winter of 2006/2007 to shorten the period of time that roads are snow or ice covered, to ease removal of snow and ice, and to assist in reducing winter weather-related vehicle crashes.

10.2.1.5. CORROSION INHIBITORS

Corrosion inhibitors may assist in delaying the onset of corrosion for spreading and plowing equipment. However, for proprietary salts that include a corrosion inhibitor, in many cases the additive is not disclosed, and therefore its effect on the surrounding environment is not known. Based on the reviewed literature, evidence of effectiveness of corrosion inhibitors outside of the laboratory was not found, and it is noted that the dilution of concentration of a corrosion inhibitor occurs rapidly with the melting of snow and ice. As the effectiveness of corrosion inhibitors for the motoring public is inconclusive, the practice of introducing additional chemicals to the environment is questionable, especially when their exact composition is unknown. Additional study regarding the effect of the use of corrosion inhibitors to reduce corrosion to infrastructure and vehicles is suggested. CTDOT should continue to monitor the findings of other agencies and future studies on effectiveness of corrosion inhibitors before implementing their use.

10.2.2 Infrastructure

10.2.2.1. PROTECT STRUCTURES

All chloride-based deicing chemicals cause corrosion. Therefore it is very important to promote the use of materials that reduce or prohibit chloride penetration into concrete and steel structures. This includes the following:

a. Use low-permeability concretes for new bridge decks

b. Use sealers and crack sealers on new bridge decks and appropriate components to slow chloride penetration

c. Ensure proper curing of concrete to minimize micro-cracking that results in pathways for the chlorides to penetrate into a structure

d. CTDOT should re-establish a bridge painting (coatings) program for steel structures

10.2.2.2. BRIDGE CLEANING

It seems obvious that the removal of salt deposits from bridge structures would be beneficial for minimizing the impacts of these chemicals. It is noted that the literature reviewed for this study did not provide consistent conclusive evidence that cleaning bridge decks and structures is cost-effective. This may be due both to the difficulty in quantifying the benefits of removing the salts and the long-term study periods required to validate the benefits. Therefore, the following focused approach for bridge cleaning is recommended.

a. Develop and fund a long-term bridge rinsing/cleaning program to remove chlorides as well as any debris that may hold moisture, particularly for steel portions of structures. Particular attention should be paid to parts of the structure most prone to corrosion such as joints, support ends, fasteners, drainage structures and steel components.

b. Remove a majority of the chlorides during the spring, when stream flows are typically higher than other times of the year, to minimize environmental impacts

10.2.2.3. BRIDGE MAINTENANCE

CTDOT and municipalities should continue to utilize best management practices for bridge maintenance, including the following:

a. Maintain bridge joints to limit water infiltration into bridge structures.

b. Minimize runoff containing chlorides from penetrating the bridge structures.

c. Perform periodic bridge inspections in accordance with the National Bridge Inspection Standards 23 CFR 650 and schedule maintenance to address deficiencies such as cleaning, minor repairs, and maintenance of proper coatings on bridge steel in a timely manner.

d. Encourage use of bridge preservation and preventive maintenance strategies. CTDOT should provide technical guidance to municipalities to assist with implementing bridge preservation programs.

10.2.2.4. CORROSION-RESISTANT DESIGNS

During the design of bridges and for bridge rehabilitation projects, consider the use of anti-corrosion materials such as

a. epoxy-coated reinforcing steel in structure elements coming in contact with deicing materials such as bridge decks, concrete barriers, and drainage structures;

b. stainless or galvanized steel rebar in critical concrete structures; and

c. corrosion-resistant materials in curbs, median barriers, catch basins.

10.2.3 Vehicles

10.2.3.1. VEHICLE WASHING

An April 2015 National Highway Traffic Safety Administration (NHTSA) Safety Advisory recommended that vehicles older than the 2008 model year be washed as soon as possible after exposure to salt and chemicals. This safety advisory was considered in developing the following recommendations.

a. Vehicle washing be performed on all classes of vehicles, from commercial trucks to motorcycles, to dilute the effects of residual deicing chemicals. Washing should assist with the prevention of corrosion for all vehicles, regardless of age.

b. If salt neutralizers are used to wash vehicles, select products that have proven to be effective. Caution should be exercised in product selection, as research reviewed for this study found that some neutralizers used at the manufacturer's recommended concentration actually increased corrosion of some metals.

c. An emphasis should be placed on rinsing/washing the undercarriage of the vehicle.

10.2.3.2. COMMERCIAL CAR WASHES

Commercial car washes should be encouraged to voluntarily disclose/post information regarding whether recycled water or fresh (clean) water is used for the car wash, particularly for undercarriage washes. If recycled water is used, then the percent of recycled water used, what cycles the recycled water is used for, and any additives used should be disclosed. Additionally it is suggested that the Connecticut General Assembly and/or Connecticut Department of Consumer Protection and Department of Energy and Environmental Protection consider regulations requiring the disclosure and posting of information on the use of recycled water for car washes.

a. Use of fresh water is encouraged for the final rinse – both on the surface and undercarriage washes.

b. Research is needed to identify acceptable salt concentrations of recycled water – that which would not be detrimental to vehicles.

Additionally, the development of additional commercial large truck/vehicle washing stations open to the public should be encouraged, as only one or two commercial large truck/vehicle washing stations are currently available in Connecticut.

10.2.3.3. CORROSION-RESISTANT TECHNOLOGY

The purchasers of commercial vehicles need to encourage vehicle manufacturers to continue to improve corrosion resistance of vehicles. This includes the use of composites, aluminum, paints and coatings, fasteners, and shrouding of critical electrical or mechanical vehicle components.

a. Use improved coatings for vulnerable components, including undercoating technologies.

b. Improve designs to eliminate known corrosion problems and areas where deicing chemicals can collect.

c. Eliminate areas where dissimilar metals come into contact with each other.

10.2.3.4. VEHICLE INSPECTIONS

There is a need for periodic voluntary undercarriage inspections of all vehicles (including passenger and commercial vehicles), particularly as vehicles age. This could possibly be performed during oil changes or other standard vehicle maintenance procedures. Other states have safety inspection programs that are required as part of the registration renewal process. Inspections could help prevent vital component failures such as brake lines or parts of the suspension system.

10.2.4 Environment

10.2.4.1. GENERAL CONSIDERATIONS FOR CHLORIDES

The use of deicing materials for winter highway maintenance has a variety of environmental impacts, some of which are more manageable than others. Some impacts are short term or seasonal, such as sudden spikes of chloride levels in soils, shallow groundwater or streams due to the flushing of deicing materials from those environments over time. Some impacts from chlorides are longer term, such as the increasing levels of chloride observed in groundwater over the past several decades. The impacts on roadside vegetation are very difficult to mitigate. Therefore any plantings (preferably native) along roadsides should have a tolerance for salt.

10.2.4.2. CHLORIDE-SENSITIVE ENVIRONMENTS

CTDOT as well as local municipalities need to periodically consult with DPH and DEEP to identify sensitive environments or drinking water sources that are at risk of impairment due to chlorides. After identifying these locations, CTDOT and the local municipalities can work to reduce the application rates of chlorides in these areas. In these identified areas, it is suggested that signs be posted for safety purposes that identify areas where application rates of deicers will be reduced for environmental or public health reasons.

10.2.4.3. MULTI-CHEMICAL APPLICATION

Although other states such as Minnesota have developed the capability to switch chemicals on the fly, typically for applying alternative chemicals in environmentally sensitive areas, no current need was identified to date in Connecticut. This technology, however, should be monitored for possible future implementation in specifications for purchase of new winter maintenance vehicles.

10.2.4.4. SALT STORAGE

Covered salt sheds have been implemented statewide by CTDOT and virtually all municipalities. However, commercial salt storage may be an issue that deserves continued attention by DEEP or DPH.

10.2.4.5. SHARED RESPONSIBILITY

CTDOT in collaboration with DEEP should inform all parties involved with winter weather-related maintenance (i.e., state, municipal, commercial, private, and consumers) of and use bestmanagement practices to protect the environment.

10.2.4.6 REPORTING OF DEICERS APPLIED

Each transportation agency within Connecticut responsible for applying deicing chemicals should be required to report the quantity of materials applied during each winter season, and this information should be made available to the public. This will enable the public to better understand the types and quantities of materials being applied. By making this information public, it will allow municipalities to see how they compare to other municipalities that they would consider comparable in both size and climate. Disparities can be identified and used as a guide to improve practices and performance.

10.2.5 Outreach and Education

10.2.5.1. PUBLIC INFORMATION CAMPAIGN

CTDOT should develop a public service campaign that utilizes web-based and social media tools along with printed materials to educate the motoring public about winter highway maintenance operations and practices. This information would help explain

a. anti-icing procedures

b. chemicals in use (and why they are used)

c. level of service goals by road type (drivers typically have an expectation that roads will be clear several hours after a storm ends, but there are conditions for some winter weather events when this is not possible)

Additionally, CTDOT, with assistance from DEEP, should develop a handbook that provides guidance for best practices for winter maintenance of sidewalks and parking lots for the general public, businesses, and private winter maintenance service companies. Consideration should also be given to limiting liability for property owners when they have followed the established best practices pertaining to slip and fall accidents. Currently, the financial cost for applying copious amounts of deicing chemicals is far less than the costs associated with a single slip and fall injury claim.

10.2.5.2. MEDIA

The media is a source of information for the general public. However, the information shared with the public needs to be accurate. Informal information indicates that the general public believes that pre-treatment chemicals applied on roadways prior to winter weather events by CTDOT contain something other than what is actually used — a 23% solution of sodium chloride in water. Both natural processes and events cause corrosion to vehicles and infrastructure as well as chemicals used for winter highway maintenance by CTDOT, municipalities, and private winter maintenance activities.

Annual informational sessions conducted in advance of the winter season for the media about winter maintenance practices, and materials that will be used for pre-treatment and anti-icing would help to dispel misconceptions. Informational sessions with the media, along with the availability of public information, will be useful in assuring factual information is distributed to the public. This will help to inform and clarify misconceptions regarding winter highway maintenance practices and materials that are used by CTDOT and municipalities.

10.2.5.3. RECORDKEEPING AND TRANSPARENCY

CTDOT and municipalities should each prepare an annual summary that accurately documents winter maintenance practices and the type of materials and quantities used for each winter season. The annual summaries should be publicly available and easily accessible.

a. CTDOT should make winter maintenance information readily available to the public via CTDOT's website. Other states, such as Maine, Minnesota, and Vermont, should be used for examples of best practices for transparency and information dissemination.

b. CTDOT should provide technical assistance and guidance to assure that the state's municipalities implement winter maintenance best practices for the 82% of the state's road network that is maintained by the municipalities.

c. Accurate recordkeeping is paramount to optimizing the use of deicers. Municipal data collected as part of this study indicates that it is possible that the towns are using greater amounts of magnesium chloride per ton of solid deicer than CTDOT. However, since there is no single repository or common format used for data collection, total material usage is not readily available. A repository for the collection of winter maintenance practices and material usage using a common reporting format should be developed.

d. Annual CTDOT and municipality winter maintenance information and data will provide an opportunity for comparisons and benchmarks between agencies for the purpose of continually improving operations throughout the state.

10.2.5.4. VOLUNTARY CERTIFICATION OF PRIVATE CONTRACTORS APPLYING DEICING CHEMICALS

The development of a voluntary certification program for private contractors who apply de-icing chemicals will be an opportunity to provide information and training to private contractors about best practices, including application rates. Certification programs of others such as the New Hampshire Department of Environmental Services' voluntary certification program for private contractors or the American Public Works Association program could be used as models for developing a Connecticut program. This certification could be used by private contractors to promote their business as being environmentally friendly regarding the application of deicing chemicals, and could be useful to businesses and the public in selecting contractors who are sensitive to the environmental issues. This certification could also be a requirement as part of limiting liability associated with slip and fall injury claims, as it is in New Hampshire.

The actual quantity of deicing chemicals applied by private contractors in Connecticut is unknown. However, information for New Hampshire indicates that the quantity of deicing chemicals used by private contractors in New Hampshire may approach half the total deicing chemicals applied in the state. With private contractors representing such a large percent of material being applied, private contractors represent a significant opportunity to reduce the quantity of salt material used in Connecticut.

10.2.5.5. COMMUNICATION

CTDOT should continue to communicate with neighboring states regarding winter highway maintenance best practices and operations. CTDOT should also continue its practice of communicating with neighboring states with regard to approaching winter weather events in order to provide as much lead time as possible for staging personnel and equipment.

Also, CTDOT should seek to communicate with municipalities with regard to information on weather, equipment, technology and best practices. In addition to CTDOT, organizations that can help to maximize outreach include the Connecticut Technology Transfer Center at UConn, CASHO, and others.

10.2.5.6. TRAINING

Initial and ongoing annual training on the best practices and methodologies should be provided for all CTDOT and municipal employees, and contractors involved in winter highway maintenance operations. This training should include

a. current state-of-practice

b. information about new technology

c. forums to discuss successes and problems encountered

This training can be provided by the Connecticut Technology Transfer Center at UConn, as well as in-house by CTDOT and others.

10.2.6 General

CTDOT should continue to monitor state-of-the-art techniques for winter maintenance and communicate with surrounding states about their winter maintenance practices. CTDOT should be cognizant of alternative chemicals that become available that might become acceptable substitutes for chlorides. Approaching any changes in the use of deicing chemicals regionally may help vehicle manufacturers design and modify their products to be more corrosion resistant, since each type of deicing chemical may have different effects on the various metals that are used in a vehicle.

10.2.6.1. LEVEL OF SERVICE

CTDOT should consider revising their definitions of levels of service for winter weather events on the three classes of state roadways that are maintained by CTDOT. Defining the level of service for the different roadway classes provides an opportunity for CTDOT to re-evaluate its policy of using a standard deicer application rate 200 lbs./lane-mile. Utilizing variable application rates under differing conditions and roadway classifications may ultimately be more cost-effective and useful in helping to mitigate the negative impacts of using chloride-based deicers. Communicating with the public about road condition expectations following a winter weather event for the different classes of roadways, setting goals, and posting achievements may be useful for maintaining reasonable public expectations.

10.2.6.2. PERFORMANCE MEASURES

CTDOT should monitor in-process studies being undertaken by NCHRP Project 14-34 “Guide for Performance Measures in Snow and Ice Control Operations” [152] and Clear Roads Project 14-05 “Snow Removal Performance Metrics” for use in developing winter highway maintenance performance measures on mobility, chemical use, and cost similar to that done in some other states. A review of performance measures implemented by other states is also recommended.

10.2.6.3. WEATHER MONITORING

RWIS are in use and assist CTDOT with storm monitoring throughout Connecticut. CTDOT plans to add an additional 23 RWIS stations to its RWIS network of stations over the next two to five years. CTDOT should

a. continue sharing weather data with/from surrounding states (MA, NY, RI);

b. share RWIS data and other information about weather events with Connecticut municipalities;

c. consider making RWIS data available to the public via a website; and

d. consider working with other states in the Northeast to provide RWIS data online using a system such as the Meteorological Assimilation Data Ingest System (MADIS) maintained by the Federal Highway Administration and the National Weather Service, as this may benefit municipalities that are located near state borders.

10.2.6.4. WINTER SEVERITY INDEX (WSI)

CTDOT should develop a WSI. While this is a challenging task, it provides a method to compare winter seasons and develop performance measures. States that have developed a WSI, including Massachusetts and Utah, can be used as references for CTDOT.

10.2.6.5. ROAD CONDITION INDEX (RCI)

CTDOT should consider developing a RCI that would be available on a regional basis during a winter weather event for state roads. This would allow CTDOT to provide information directly to the public. One of the most important and difficult aspects of this would be the need to keep the information current during a winter weather event. Utah DOT has a RCI that could be used as a guide for CTDOT.

10.2.6.6. CLEAR ROADS CONSORTIUM

CTDOT should continue their participation in the Clear Roads consortium pooled fund project. Participating in these groups enables CTDOT to be aware of ongoing research and new products. CTDOT should participate in Clear Roads field trials if possible and appropriate.

10.2.7 Equipment

10.2.7.1. GROUND SPEED CONTROLLERS

The inclusion of ground speed controllers for deicing chemical application on all new equipment purchases should be considered standard practice to ensure that the desired application rates are achieved. Ground speed controllers are installed on virtually all of CTDOT's material spreading equipment, and it is recommended that municipalities do the same.

10.2.7.2. CALIBRATION OF SPREADERS

The calibration of material spreaders should be performed at least on an annual basis or as required, which is the current practice of CTDOT and mnay municipalities. Accurate record keeping will be useful for determining if a specific piece of equipment is applying a radically different amount of material than expected. This may be an indication that the spreader needs to be recalibrated. It is also suggested that spreaders should be calibrated two to three times during the winter season, as well as after any repairs are performed.

10.2.7.3. SALT SLURRY SPREADERS

Salt slurry spreaders have been successful at improving the application of salt materials. CTDOT purchased salt slurry spreaders to test this technology in Connecticut. Initially, the testing involved setting up the equipment to apply the desired amount of material. It is expected that these spreaders will be tested in operation in the winter of 2015/2016.

Similar to the process noted above, an example of a process or steps suggested for implementation of other new technologies is as follows:

- First, demonstrate the product.
- Next, test the product in operation under actual conditions typically experienced.
- Finally, follow with operational implementation and monitoring to assure that the results are those that are expected.

10.2.7.4. GPS AND MATERIAL DATA LOGGERS

The technology exists to track the location of deicing chemical-spreading vehicles via GPS while at the same time recording spreading equipment settings. This data can be used to develop a very detailed material application tracking system. These types of systems require analysis of the data and can generate a great deal of data depending on how they are configured. Therefore, before implementing this type of system, it is necessary to determine how this data will be managed, as well as how it will be used for monitoring and improving performance, as well as decision making.

10.2.7.5 MULTI-SECTIONAL PLOWS AND UNDERBODY SCRAPERS

Multi-sectional plows improve plowing performance on uneven roads. Underbody scrapers are useful for maximizing snow removal on roadways with packed snow and ice. These technologies should be considered for plowing operations since plowing is the most environmentally friendly method for snow and ice removal—the more snow and ice that is removed mechanically, the less deicing chemicals needed. Currently, CTDOT uses underbody scrapers on a limited basis, and reportedly underbody scrapers and multi-sectional plows are used by several municipalities.

10.2.7.6 APPLYING AND VERIFYING APPLICATIONS

Technological improvements that should be considered for winter maintenance operations to maximize deicing chemical application efficiency include

a. measuring and weighing loads of deicing chemicals and abrasives to accurately track the amount of materials used; and

b. pavement and air temperature sensors for all trucks that can be used for decision making for varying application rates based on current and forecasted conditions.

10.3 SUMMARY

Sustainable winter maintenance operations are achieved by balancing the demands of the users, the available budget, and the environment. Chloride-based deicing chemicals will continue to be the most common deicer used for winter highway maintenance operations. While chloride-based deicers are effective at helping transportation agencies remove snow and ice from roadways, which assists in providing the traveling public with safe roadways and mobility as soon as possible following a winter weather event, their use also contributes to increased corrosion of infrastructure and vehicles, as well as possible environmental impacts.

Therefore, under the assumption that safety and mobility of the traveling public are key goals of winter highway maintenance operations, it is necessary for everyone to recognize that minimizing the negative impacts of the use of chemical deicers is a shared responsibility.

- For transportation agencies, this includes achieving the maximum benefit from the least amount of chemical deicer application, and assuring that best practices are utilized for operations.
- For the general public and commercial vehicle owners and operators, this includes washing vehicles after each winter weather event to remove as much deicing chemical as possible; inspecting the undercarriages of vehicles periodically for damage due to corrosion of critical safety components; and having reasonable expectations for the return of roadways to a safe condition following a winter weather event.

As previously noted in this report, the DOTs of the states surveyed for this study are responsible for maintaining different types of roadways, with different levels of service being required. Additionally winter weather events vary from state to state. These factors make state to state comparisons of deicer chemical usage and practices useful only as a frame of reference for use by each state in seeking to continually improve winter maintenance operations. Taking this into consideration, CTDOT's total application of chlorides per lane-mile is typically lower than that of the other surveyed northeastern states.

It is important for CTDOT to continually monitor, review and implement winter highway mainteance best practices including operations, technological advances, and use of improveddeicing chemicals to maximize efficiency and reduce adverse effects on infrastructure, vehicles, and the environment while maintaining public safety and mobility.

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APPENDIX A
GLOSSARY OF TERMS

Anaerobic: An environment lacking oxygen

Anions: A negatively charged atom or group of atoms

Anti-icing: A non-mechanical process by which a liquid chemical, usually salt brine, is applied to a roadway prior to or very early in a winter weather event. The chemical is applied to prevent bonding of snow and ice to the pavement surface by lowering the freezing point at which this occurs [1]

Calcium Silicate Hydrate (C-S-H): Formed by Portland Cement within Portland Cement Concrete during initial curing after construction to add strength to the concrete

Capitol Region Council of Governments (CRCOG): A Connecticut planning region comprising 38 municipalities in the metropolitan Hartford area

Cathodic Protection: A technique used to control the corrosion of a metal surface by making it the cathode of an electrochemical cell

Cations: Positively charged ions that are formed when an atom loses one or more electrons during a chemical reaction

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. [53]

CTDOT Highway Operations Centers: CTDOT's operations centers, located in Newington and Bridgeport, monitor traffic and weather conditions 24/7 and support the CTDOT storm center during severe winter weather. These monitoring operations include utilizing 324 available traffic cameras statewide, as well as communicating with the State Police on weather related incidents that occur, and apprising the storm monitors and the operation managers.[4]

CTDOT Snow and Ice Control Standing Committee: This committee was formed in 2006 and named as a standing committee in 2015. The committee comprises personnel from the Bureau of Highway Operations and Maintenance, the Bureau of Policy and Planning, Environmental Planning Division, and the Bureau of Finance and Administration. The committee meets monthly to provide input and review of the winter maintenance process, including discussion and critique of snow and ice related issues and concerns, environmental policy and materials. [4]

CTDOT Storm Monitors: CTDOT Office of Maintenance staff serve as both the central point of contact for notification of pending winter weather events and coordinators for reporting staffing and equipment information and field weather conditions during winter weather events. [4]

CTDOT Storm Center: The CTDOT Storm Center, located at CTDOT Headquarters in Newington, CT serves as the center of operations during storms and events.[4]

Deicing: A strategy by which ice and/or compacted snow is removed from the roadway by either a chemical or mechanical means or a combination of the two. This includes chemical treatments, such as salt, which are applied later in a winter storm and continued past the end of the storm. [1]

Deliquescence: The process by which a substance absorbs moisture from the atmosphere until it dissolves in the absorbed water and forms a solution.

Echelon Plowing: Snow plowing in tandem, with plows staggered in a formation to cover all lanes of a roadway.

Endothermic Reaction: A reaction where heat energy is absorbed from surrounding materials

Eutectic Temperature: The optimum eutectic temperature for a given product is the lowest temperature at which a product will freeze when at the optimum ratio of chemical to water. This can also be stated as the lowest freeze-point achievable by a given chemical through an optimum ratio of chemical to water.

Evapotranspiration: The sum of evaporation and plant transpiration from the Earth's land and ocean surface to the atmosphere.

Exothermic Reaction: A chemical reaction that releases energy in the form of heat.

Gore Area: A triangular-shaped boundary marked by white lines intended to help organize and protect traffic when vehicles enter or exit highways. Gore areas separate an exit ramp from the through lanes on a highway and assist drivers to safely merge on or off an exit ramp.

Ground Speed Controller: Systems that automatically change application rate with change in ground speed

Halite: Rock salt – sodium chloride

Hygroscopic: A substance that absorbs moisture from the air under certain conditions of humidity and temperature but not necessarily to the point of dissolution

Inorganic Chemical Deicer: All salts are inorganic and non-biodegradable. Three inorganic chloride deicers (magnesium chloride, sodium chloride and calcium chloride) are discussed in this report.

KABCO Injury Scale: A system to classify victims from crashes: *"where K–killed, A–incapacitating injury, B–non-incapacitating injury, C–possible injury, or O–no apparent injury"* used by many state public safety offices for accident coding [148]

Lane-Mile: 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 [53]

Level of Service: a qualitative measure used to relate the quality of traffic service defined by six levels:

A: Free flow, low traffic density

B: Minimum delay, stable traffic flow

C: Stable condition, movements somewhat restricted due to higher volumes, but not objectionable for motorists

D: Movements more restricted, travel speeds begin to decline

E: Traffic fills capacity of the roadway, vehicles are closely spaced, incidents can cause serious breakdown

F: Forced flow with demand volumes greater than capacity resulting in breakdown in traffic flow

Linear Referencing System: A method of spatial referencing, in which the locations of features are described in terms of measurements along a linear element, from a defined starting point; for example, a milepoint along a road. Each feature is located by either a point (e.g. a signpost) or a line (e.g. a no-passing zone). The system is designed so that if a segment of a route is changed, only those milepoints on the changed segment need to be updated.

Magnesium Silicate Hydrate (M-S-H): Formed in Portland Cement Concrete from a chemical reaction with magnesium chloride. MSH is a powder or gel substance with limited strength and is thus deleterious to the concrete. [21]

MAIS Injury Scale: The maximum Abbreviated Injury Scale (AIS) is an anatomically based, severity scoring system that classifies each injury by body region according to its relative importance on a 6-point ordinal scale (1=minor and 6=maximal). The AIS was developed by the Association for the Advancement of Automotive Medicine (AAAM). See www.aaam1.org/index.html [148]

Molal: One mole of solute in 1 kg of solvent

Molality: The number of moles of solute per kilogram of solvent. It is important that the mass of solvent is used and not the mass of the solution. Solutions labeled with molal concentration are denoted with a lower case "m". A 1.0 m solution contains 1 mole of solute per kilogram of solvent.

Molar: Relating to 1 mole of a substance (1.0 M = one mole per liter)

Molarity (*also known as molar concentration*)**:** The number of moles of a substance per liter of solution. Solutions labeled with the molar concentration are denoted with a capital M. A 1.0 M solution contains 1 mole of solute per liter of solution.

Necrosis: The death of living cells or tissue or the morphological changes indicative of cell death. When plants are subjected to abiotic stress they initiate rapid cell death with necrotic morphology.

Non-intrusive Remote Temperature Sensor: A hand-held or vehicle attached sensor that can read the surface temperature of pavement on a continuous basis.

Organic Chemical Deicer: Deicer compounds that contain carbon are organic. Organic biodegradable deicers described in this report include: urea, propylene glycol, potassium formate, sodium formate, potassium acetate, calcium magnesium acetate, sodium acetate, and agricultural by-products such as beet juice, molasses, corn syrups, and others.

Osmotic Stress: A sudden change in the solute concentration around a cell causing a rapid change in the movement of water across its cell membrane. Under conditions of high concentrations of salts, water is drawn out of the cells through osmosis.

Oxychlorides: A compound having oxygen and chlorine atoms bonded to another element

pH: A measurement of a solution's acidity or alkalinity

Pre-treating: The application of either a liquid chemical such as salt brine, a dry solid chemical salt or a pre-wetted solid mixture of chemicals to the pavement surface prior to the start of a winter weather event. Pre-treating is a proactive preventative strategy to decrease the possibility of snow bond, black ice from freezing rain or frost formation on pavement surfaces. Pre-treating is a form of anti-icing.

Pre-wetting: The process by which a liquid chemical (usually salt brine or water) is added to a [solid] deicer chemical prior to application to the roadway. Pre-wetting can occur at different points in the application process and different equipment options are used on the trucks. [1]

Road Weather Information Systems (RWIS): FHWA defines a RWIS as comprising environmental sensor stations (ESS) in the field, a communication system for data transfer, and central systems to collect field data from numerous ESS. ESS stations measure atmospheric, pavement and/or water level conditions. Central RWIS hardware and software are used to process observations from ESS to develop nowcasts or forecasts, and display or disseminate road weather information in a format that can be easily interpreted and used by road operators and maintainers to support decision making.

Rock Salt: Composed primarily of sodium chloride, and used as a deicer for snow and ice control

Salt Brine: A liquid solution of salt, most commonly sodium chloride and water; as used in this report salt brine is 23% sodium chloride with water in solution.

Salt Neutralizing Agent: A product applied to a vehicle surface to reduce corrosion from salts, and once left on to air dry, leaves a protective coating for further protection from corrosion. Can lengthen the life of assets by reducing corrosion damage and improving performance.

Salt Slurry Generation Applicator: A proprietary device attached to the back of a chemical application truck used for winter highway maintenance that reduces salt grain size, increases moisture and allows for deicers to be applied at more grains per square foot than conventional distributors.

Silane sealer: A penetrating sealer used to seal materials such as dense concrete to repel water

State Emergency Operations Center: The Center is located in Hartford. During storms and emergencies the Center is headed by Connecticut's Governor and staffed with state emergency management personnel and representatives of the state's major utility companies.

Toxicosis: Any diseased condition due to poisoning

Vehicle Miles of Travel (VMT): A measurement or sum of total miles traveled by all vehicles in a specified region for a specified time period. CTDOT usually reports VMT as average daily VMT or average annual VMT. For example if there are 3 million vehicles each travelling 10 miles per day, the daily VMT equals 3 million X 10 = 30 million daily VMT.

Winter Activity *(CTDOT def.)***:** Winter weather events are defined by CTDOT as activities and storms. Activities typically last less than six hours and involve less than 50% of the workforce.

Winter Storm *(CTDOT def.)***:** Winter weather events are defined by CTDOT as activities and storms. Storms are of longer duration than activities with more than 50% of the snow and ice control workforce activated.

APPENDIX B
STUDY COMMITTEE MEETINGS AND GUEST SPEAKERS

The following is a list of study committee meetings, including presentations by guest speakers and the CASE Research Team. In the electronic version of this report, links to meeting presentations are highlighted in blue.

JULY 17, 2014 – MEETING 1

- **Welcome and Introductions**
- **Previous CASE Study**
  Richard Strauss, CASE Executive Director
- **Guest Presenters**
  Mike Riley, President, Motor Transport Association of Connecticut
  Kim Pelletier, Truck Builders
  Topic: Truck Corrosion
- **CTDOT Presentation Introduction of Study Topic -**
  Charles Drda, Transportation Maintenance Administrator, Office of Maintenance
  Topic: Introduction of Study Topic – Presentation
- **Research Team – Plan for Study**
  Jim Mahoney (CASE Study Manager), Executive Program Director, Connecticut Transportation Institute, UConn – Presentation
- **Next Steps**

SEPTEMBER 17, 2014 – MEETING 2

- **Welcome and Introductions**
- **Guest Presenters**
  Mark Hammerlein, Water Quality Program Manager, New Hampshire DOT
  Topic: NHDOT Chloride Issues, Challenges and Solutions – Presentation
  Eric Williams, Watershed Assistance Section Manager, New Hampshire Department of Environmental Services – Presentation
  Topic: New Hampshire Road Salt Reduction Initiative
- **Study Committee Member Presenter**

  Paul Brown, Director of Snow and Ice Operations, Massachusetts Department of Transportation
  Topic: Massachusetts Winter Highway Maintenance Practices - Presentation

- **Research Team Update**
  Jim Mahoney, Study Manager – Presentation

- **Next Steps**

OCTOBER 21, 2014 – MEETING 3

- **Welcome and Introductions**

- **Guest Presenter**
  Joe H. Payer, Chief Scientist, National Center for Education & Research for Corrosion & Materials Performance, Corrosion and Reliability Engineering, University of Akron
  Topic: Corrosion Cost and Preventive Strategies in the US – Presentation, Appendix

- **Guest Presenter**
  David Darwin, Deane E. Ackers Distinguished Professor and Chair, Department of Civil, Environmental Architectural Engineering, University of Kansas
  Topic: Effects of Deicers on Concrete Deterioration – Presentation

- **Study Committee Member Presenter**
  Monty Mills, Maintenance & Operations Branch Manager, Washington State DOT
  Topic: Corrosion to Snow & Ice Material Application Equipment – Presentation

- **Research Team Update**
  Jim Mahoney, Study Manager

- **Next Steps**

NOVEMBER 14, 2014 – MEETING 4

- **Welcome and Introductions**

- **Study Committee Member Presenter**
  Brian Burne, Highway Maintenance Engineer, Maine Department of Transportation
  Topic: Maine Winter Highway Maintenance Practices – Presentation

- **Guest Presenter**
  Western Transportation Institute, Montana State University: **Laura Fay**, Research Scientist, Winter Maintenance & Effect Program Manager and **Mehdi Honarvar Nazari**, Postdoctoral Visiting Scholar
  Topic: Corrosion Inhibitor Research – Fay Presentation, Nazari Slide

- **CTDOT Presentation**
  Charles Drda, Transportation Maintenance Administrator, Office of Maintenance
  Topic: ConnDOT Winter Highway Maintenance Practices – Presentation

- **Research Team Update**
  Jim Mahoney, Study Manager – Presentation

DECEMBER 17, 2014 – MEETING 5

- **Welcome and Introductions**
- **Guest Presenter**
  Chelsea Monty, Assistant Professor, Chemical and Biomolecular Engineering, University of Akron
  Topic: Research on the Effectiveness of Salt Neutralizers for Washing – Presentation
- **Guest Presenter**
  Bob Hamilton, Director of Fleet Maintenance, Bozzuto's, Inc.
  Topic: Winter Weather Fleet Management – Presentation
- Guest Presenter
  Daniel Szczepanik, OE/Commercial Products Manager, Sherwin-Williams
  Topic: Protecting Vehicles from Corrosion – Presentation
- **Research Team Update**
  Jim Mahoney, Study Manager -- Presentation, Handout: Commercial Car Washes, Handout: Cargill MSDS, Handout: Sodium Chloride Health
- **Next Steps**

JANUARY 21, 2015 – MEETING 6

- **Welcome and Introductions**
- **Guest Presenter**
  J. Adam Hill, Vice President of Product Sales Engineering**,** Great Dane Trailers
  Topic: Corrosion Issues – Presentation
- **Research Team Update**
  Jim Mahoney, Study Manager – Presentation
- **Committee Discussion**
  Rick Strauss, Executive Director
  Topic: Brainstorming concepts for recommendations
- **Next Steps**

MARCH 11, 2015 – MEETING 7

- **Welcome and Introductions**
- **Guest Presenter**
  Stacey Spencer, Principal Engineer**,** Global Technology Specialist Materials Engineering**,** Volvo Group Trucks
  Topic: Effect of Deicers on Engineering of Class 8 Trucks – Presentation

- **Guest Presenter**
  Jeff Williams, Weather Operations Manager, Utah Department of Transportation
  Topic: Utah Severity Index – Presentation

- **Research Team Update**
  Jim Mahoney, Study Manager – Presentation, Handout 1, Handout 2

- **Guest Presenter**
  Michaela Cisowski, Northwestern Regional High School, District #7, Winsted, CT
  Topic: Rust in Peace – Uninhibited Magnesium Chloride Brine – Presentation

- **Committee Discussion**
  Richard Strauss, Study Manager
  Topic: Brainstorming findings and concepts for recommendations

- **Next Steps**

APRIL 10, 2015 – MEETING 8

- **Welcome and Introductions**

- **Guest Presenter**
  Bob Rossini, Incoming President, Connecticut Carwash Association
  Topic: Winter Road Maintenance Practices - Carwash

- **Research Team Update**
  Jim Mahoney, Study Manager – Presentation
  Kay Wille, Research Team
  Topic: Effects of Deicer Corrosion on Infrastructure – Presentation
  Tim Vadas, Research Team
  Topic: Environmental Impacts of Deicing Chemicals – Presentation

- **Committee Discussion**
  Richard Strauss, Executive Director, CASE
  Topic: Brainstorming findings and concepts for recommendations

- **Next Steps**

MAY 5, 2015

- **Welcome**

- **Committee Discussion**
  Richard Strauss, Executive Director, CASE
  Topic: Brainstorming draft findings and recommendations

- **Next Steps**

APPENDIX C
AN OVERVIEW OF SNOW AND ICE CONTROL OPERATIONS ON STATE HIGHWAYS IN CONNECTICUT

JUNE 2015

This overview is intended to provide basic information on advanced snow and ice control operation practices employed on the Connecticut State highway network. It is for informational purposes only, and does not constitute a standard, policy or guideline.

Connecticut Department of Transportation
Bureau of Highway Operations
Office of Maintenance

CONNECTICUT DEPARTMENT OF TRANSPORTATION

An Overview of Snow and Ice Control Operations on State Highways In Connecticut

June 2015

This overview is intended to provide basic information on advanced snow and ice control operation practices employed on the Connecticut State highway network. It is for informational purposes only, and does not constitute a standard, policy or guideline.

Bureau of Highway Operations

Office of Maintenance

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Introduction

Snow and ice covered roads can severely impact mobility and disrupt modern societies that depend upon government services to improve public safety, provide mobility and minimize the economic impact. Advancements in anti-icing technology and practices, weather information, operational methods, materials and equipment have transformed snow and ice control to provide both improved levels of service and efficiencies on our highway system.

This overview provides basic information on the many elements, technical decisions and proactive approaches currently employed by the Connecticut Department of Transportation (CTDOT) to achieve and maintain reasonable levels of service during winter weather-related events on Connecticut's highways.

Mission

Connecticut's General Statute 13a-93 requires that "the commissioner *(Transportation)* shall remove the snow from the traveled portions of any completed state highway when the accumulation thereof renders such highway unsafe for public travel"/1/. Also, CTDOT Policy No. HO-5 (4/8/11), states "The Department shall provide a standard of winter maintenance that provides for the motoring public reasonably safe roads during and after adverse weather conditions throughout the winter season"/2/.

Effective snow and ice control operations are essential for achieving CTDOT's mission "to provide a safe and efficient intermodal transportation network that improves the quality of life and promotes economic vitality for the State and the region"/3/.

Snow and Ice Control Operations

To address the challenges associated with winter weather on the State highway network, CTDOT has charged the Bureau of Highway Operations and Maintenance with snow and ice control operations. This responsibility includes maintaining a network of over 10,800 lane-miles[1]. Snow and ice operations involve many elements, including, but not limited to: planning and analysis of plowing routes, continuous review of practices and procedures of snow states, acquisition of equipment and materials, annual snowplow operator training, weather prediction and storm tracking, as well as a thorough understanding of anti-icing, deicing, highway monitoring, and plowing practice.

CTDOT staff prepare throughout the year for snow and ice deployment between November 1st and April 30th each year. The Department's deployment strategy seeks to:

[1] Comprises 10,300 mainline and ramp lane-miles /5/ (CTDOT Planning, 2013) as well as an additional 500 lane miles from miscellaneous plowed road segments. (i.e. turn-arounds, High Occupancy Vehicle (HOV) Lanes, climbing and turning lanes, etc.) Parking lots and facilities are not included in this quantity.

- pro-actively utilize weather information, anti-icing methods and manpower;
- prescribe road treatments, based on expected and actual conditions;
- provide for continuous plowing and critical operational support throughout storm events;
- balance effective treatment with public safety, environmental concerns and cost;
- prescribe road treatments, based on expected and actual conditions; and the following highway classifications:

  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.

Anti-Icing

The anti-icing approach has been CTDOT's primary snow and ice control strategy since 2006. The goal of the anti-icing approach is to prevent the snow and ice from bonding to the pavement surface /6/. This approach actively employs weather information and utilizes the most effective methods and materials for road treatment based on specific conditions. Anti-icing treatments specifically include "Pre-Treating" and "Pre-Wetting" methods. Pre-Treating is the placement of anti-icing materials, specifically sodium chloride solution on state roads in CT, in advance of anticipated weather events. Pre-Wetting is the advanced activation of sodium chloride, commonly referred to as rock salt, by infusing a liquid chloride to the rock salt at the discharge chute /6/. The deployment strategy includes strategic timing of both the treatments and plowing, based on storm characteristics, treatment activation times, traffic patterns, and time of day. The anti-icing approach results in both improved level of service and the efficient use of chemicals /6/.

Weather Information

CTDOT receives contracted weather forecasting services that are paramount to effective decision-making. Weather reports are issued daily and in advance of adverse weather. Specific routine and emergency forecasts are provided for seven geographic zones in the State, as shown in Figure 1.

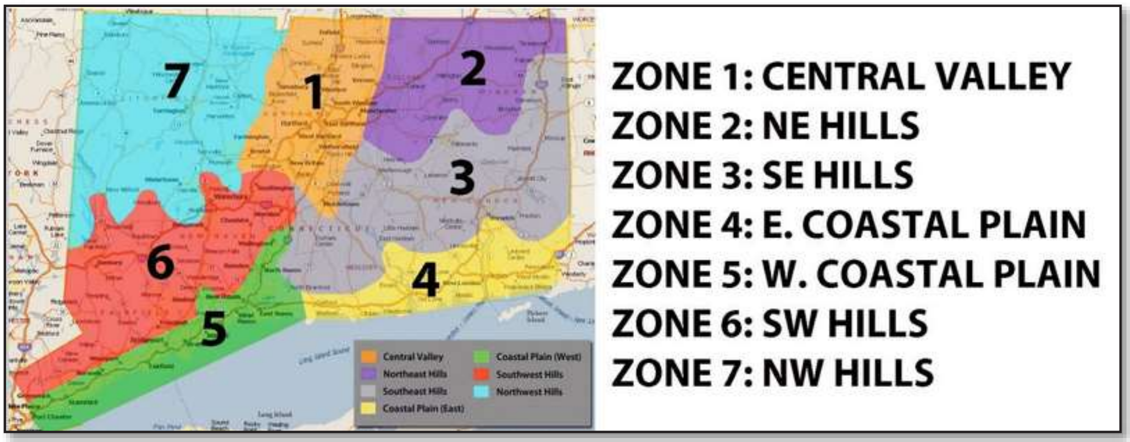

Figure 1: Map of Weather Zone Designations in Connecticut

The forecasting service report includes an array of forecasted data, including: maximum and minimum air temperatures, general cloudiness, precipitation type(s) and intensity, projected ground accumulation, timing, duration, wind direction and velocity, as well as other pertinent forecast information and remarks, including post-storm conditions. The weather service employees contact CTDOT storm monitors two hours in advance of snow and ice precipitation entering the state, and continue to issue updated advisories every four hours, or as required, until the storm event has ended. Weather forecasting information is also provided by the Division of Emergency Management and Homeland Security of the Department of Emergency Services and Public Protection during major storm events.

In addition to forecast services, actual field condition information is paramount. Pavement temperatures are essential to successful decision-making in the anti-icing deployment strategy. Field condition data are monitored from truck-mounted air and pavement temperature sensors and from Road Weather Information Systems (RWIS). There are currently thirteen RWIS installed on the Connecticut State highway network and more RWIS stations are proposed to be installed strategically throughout the network in the near future. Information from these systems provides road and bridge surface temperatures, relative humidity, dew point, air and subsurface temperatures, precipitation type and chemical concentration. Some RWIS stations are also equipped with cameras for visual verification of conditions. An RWIS weather station is shown in Figure 2 and an in-pavement sensor part of an RWIS is shown in Figure 3.

Figure 2: RWIS: Station, Route 2, Lebanon, CT (Left)

Figure 3: In-Pavement Sensor (Right)

Real-time weather conditions are observed 24/7 by highway operations personnel who have access to 324 highway traffic cameras located throughout the state. The CTDOT Highway Operations Centers are located in Newington and Bridgeport, CT.

Pre-Treating

CTDOT utilizes pre-treating in advance of winter weather events, including frost, freezing rain and snow. Pre-treating is conducted when conditions allow, as outlined by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) Guidelines /6, 7/. The decision flowchart used for pre-treatment is provided in Figure 4.

Trucks specifically equipped with tanks, called "tank trucks," are used to pre-treat bridge decks and high-risk areas with a sodium chloride brine solution. When placed under dry conditions, the brine solution, as designed, will dry and remain dormant on the treated surface for up to five days. It is activated by moisture to mitigate the ice bond at locations that may freeze first. Pre-treating serves as an immediate deployment at these locations. Without pre-treating, such a timely response is unattainable through traditional methods. In addition, this provides mobilization time and improved efficiency during non-work periods.

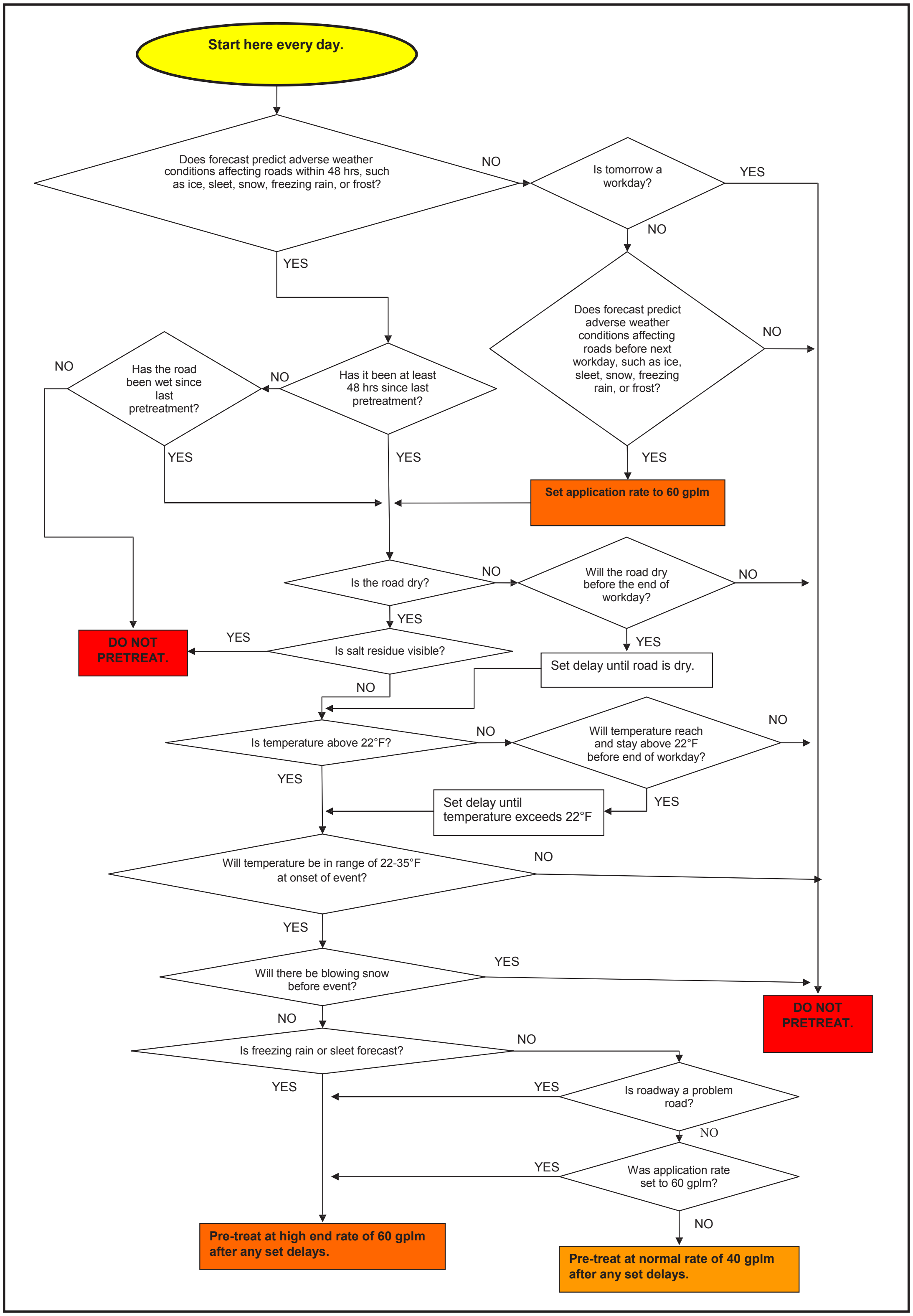

Figure 4: Decision Flowchart for Pre-Treatment in Connecticut

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Figure 5: Pavement Pre-Treated with Sodium Chloride Brine Solution

Figure 5 shows a roadway pre-treated with sodium chloride brine solution. Full application guidelines are outlined in the CTDOT Bureau of Highway Operations, Office of Maintenance Snow and Ice Guidelines /4/.The brine solution is produced at centralized maintenance facilities with water and rock salt to make a 23% sodium chloride solution. Scientifically, the 23% solution is the concentration that provides the lowest freezing point (i.e., eutectic composition) for sodium chloride/6 /. A mixing device and storage tanks used for the brine are shown in Figure 6. The amount of brine solution applied is by temperature, in accordance with CTDOT Guidelines /4/: Specifically, 30 gallons per lane-mile at 32°F[2], 40 gallons per lane mile at 22°F. It is not applied when the road temperature is below 22°F.

Figure 6: Brine Mixing (Sodium Chloride) and Storage (Sodium Chloride and Magnesium Chloride) Tanks, Putnam Garage

[2] All application temperatures refer to pavement temperatures.

During the Storm

The goal is to keep snow and ice from bonding to the pavement surface by applying sufficient material to break the ice/pavement bond. Salts are effective in breaking as well as preventing the bond of ice because of the capability to lower the freezing point of water/8/. As described by AASHTO, "salt is widely used because of its effectiveness at moderate subfreezing pavement temperatures, relatively low cost, availability, and ease of application..."/7/ (p. 31). The effectiveness of salts is temperature dependent. For most conditions (above 20°F), sodium chloride is placed at a rate of 200 pounds per lane-mile/4/.

Pre-Wetting

Pre-wetting (liquid) is a method where solution is applied to the sodium chloride (solid) to help keep the solid materials on the road by preventing bounce and scatter, and activate the salt more quickly to melt the snow and ice at lower working temperatures and reduce the overall amount of salt needed/8,9,10, 11/. The sodium chloride, rock salt, is pre-wetted at the time of placement with a magnesium chloride solution. This solution is purchased premixed and consists of 30% magnesium chloride (by weight) and 70% water (by weight)/4/. This solution is applied to the sodium chloride (rock salt), at the rate of one gallon per lanemile, as the sodium chloride is spread from the truck, as shown in Figure 7. By weight, this is approximately 3 pounds of magnesium chloride per lane-mile. A sodium chloride solution may also be used for pre-wetting at temperatures above 25°F, at the manager's discretion /4/. Calcium chloride solution was used for pre-wetting in 2006 – 2012 until supply issues were encountered.

Figure 7: Salt, Pre-Wetted as Dispensed, Using a Static Spinner to Create a Windrow Application

"Call-out" is deployment based on expected pavement temperatures, accumulation and precipitation type by geographic region(s). Deployments are most often enacted based on information received through the contracted weather service, but can also be initiated based on information from staff field

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reports, public safety offices or other agencies. At the core of the deployment process are staff designated as "Storm Monitors." They serve as both the central point of contact for notification of pending winter weather events and coordinators for reporting staffing and equipment information and field weather conditions during winter storms. They are notified two hours prior to the prediction of any precipitation in the form of snow or freezing rain entering the state and prior to a storm warning issued by the contracted weather service. The contracted weather service continues with four hour updates during an event. Four storm monitors are on-call 24 hours per day, seven days per week during the winter season.

It is the storm monitor's responsibility to notify the Highway Maintenance Managers of updated weather and roadway information, including air and road temperatures and other atmospheric conditions. Maintenance Managers are responsible for determining the type and extent of road treatment, as well as the labor and equipment needs for each deployment. The CTDOT Storm Center, located at CTDOT Headquarters in Newington, CT, serves as the center of operations during storms and events. Figure 8 shows the Storm Center during activation.

Figure 8: Activated Storm Center, Newington, CT.; (Insert) Storm Activation, Graphical Display

The State of Connecticut deploys 632 plow trucks, 120 loaders and other specialized equipment, including snow blowers, and uses over 1,100 essential employees during full activation. In addition, contractor-supplied plow trucks (approximately 200) can be called into service for additional support under Department of Administrative Services (DAS) contract, if conditions warrant. Repair facilities are activated and operational during snow and ice events to support continuous operations. The routing, lane coverage and synchronization of truck formations are well planned and orchestrated. Routings are established based on traffic volume, mileage, and round-trip cycle time. The routings are carefully planned by each district to address a variety of needs and are updated annually.

Skilled plow operators use various plow and blade configurations, spreading patterns and application rates, and planned and specific truck arrangements such as echelon plowing (depicted in Figures 9 and 10) to achieve best results.

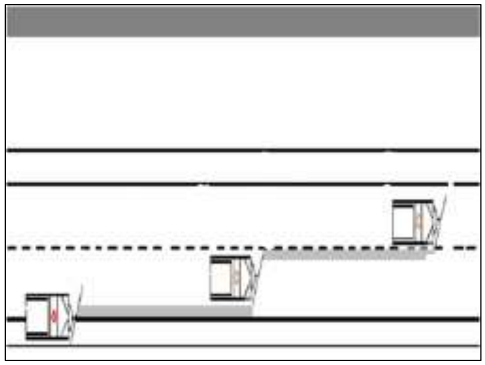

Figure 9: Echelon Plowing: Configuration

Figure 10: Trucks Deployed in Echelon

General practice is one application every three hours with variations based upon the weather conditions, traffic and time of day. For example, when the snowfall rate is extremely heavy, plows operate with the purpose of clearing travel lanes. During these conditions, it is most practical to plow the snow without applying the material. Key application times are at the beginning and ending of precipitation and prior to rush hour traffic. Contracted trucks are used to plow snow only and do not apply chemicals. A small fleet of two-axle dump trucks are also utilized to plow commuter parking lots.

Conditions during snow and ice season can vary considerably between seemingly minor to extreme weather events. It is a challenge to address the motoring public's needs based on the inexact science of weather prediction. For this reason, snow and ice professionals use various additional tools to address specific and immediate needs. When extremely severe winter conditions are encountered, the Governor may activate the Emergency Operations Center (EOC), which serves as the hub for all statewide emergency management personnel. The Governor may also declare travel bans, as necessary.

Post Storm

After precipitation has ended and the travel way is cleared, work continues to remove snow from other areas of accumulation. Such areas include pavement shoulders, bridges and viaducts,gore and ramp areas, impact attenuators, catch basins, median barriers, sidewalks which are the State's obligation for winter maintenance, and other locations where snow can melt and drain into the roadway. Department-maintained yards are cleared, and snow obscuring the visibility of warning and directional signs is removed. Removal is conducted using various equipment including industrial snow blowers, pay loaders and manual labor. Figure 11 shows industrial snow blowers in use. After each storm, all equipment is cleaned, checked, and repaired as necessary to get ready for the next winter event. Periodically during the winter season, a neutralizing agent is applied to all snow and ice equipment, per manufacturers' recommendations/12/.

Figure 11: Industrial Snow Blowers In-Use, Post Storm.

Detailed records on material usage are maintained and checked after each storm to ensure that application rates are in accordance with CTDOT guidelines. In addition, material supplies are inventoried and restocked and the budget is tracked. Figure 12 is an example of the truck operator activity log manually completed by each operator per shift. Information on material use from the truck operators' logs are summarized at the garage level into "Statewide Storm Summary Reports"/13/ (a.k.a. 'Maintenance 9 Form').

These Storm Summary Reports are submitted to staff maintenance for review as part of the maintenance management system. Tables 1 and 2 provide excerpts from the Summary Report, as examples. Table 1 details how the hours, sand, salt and chloride (magnesium) were recorded by section throughout the season (this example: Storm #8, 2012/2013 Season.) Summaries are also provided by District and by crew. Table 2 details how materials are recorded by crew. Further breakdown of these amounts are listed by two-lane, ramp, multi-lane and post-secondary categories. Table 3 lists the estimated material usage from CTDOT from 2000 - 2014. Material usage is highly dependent upon many factors that are not listed, including storm intensity, temperature and time of day. For example, the

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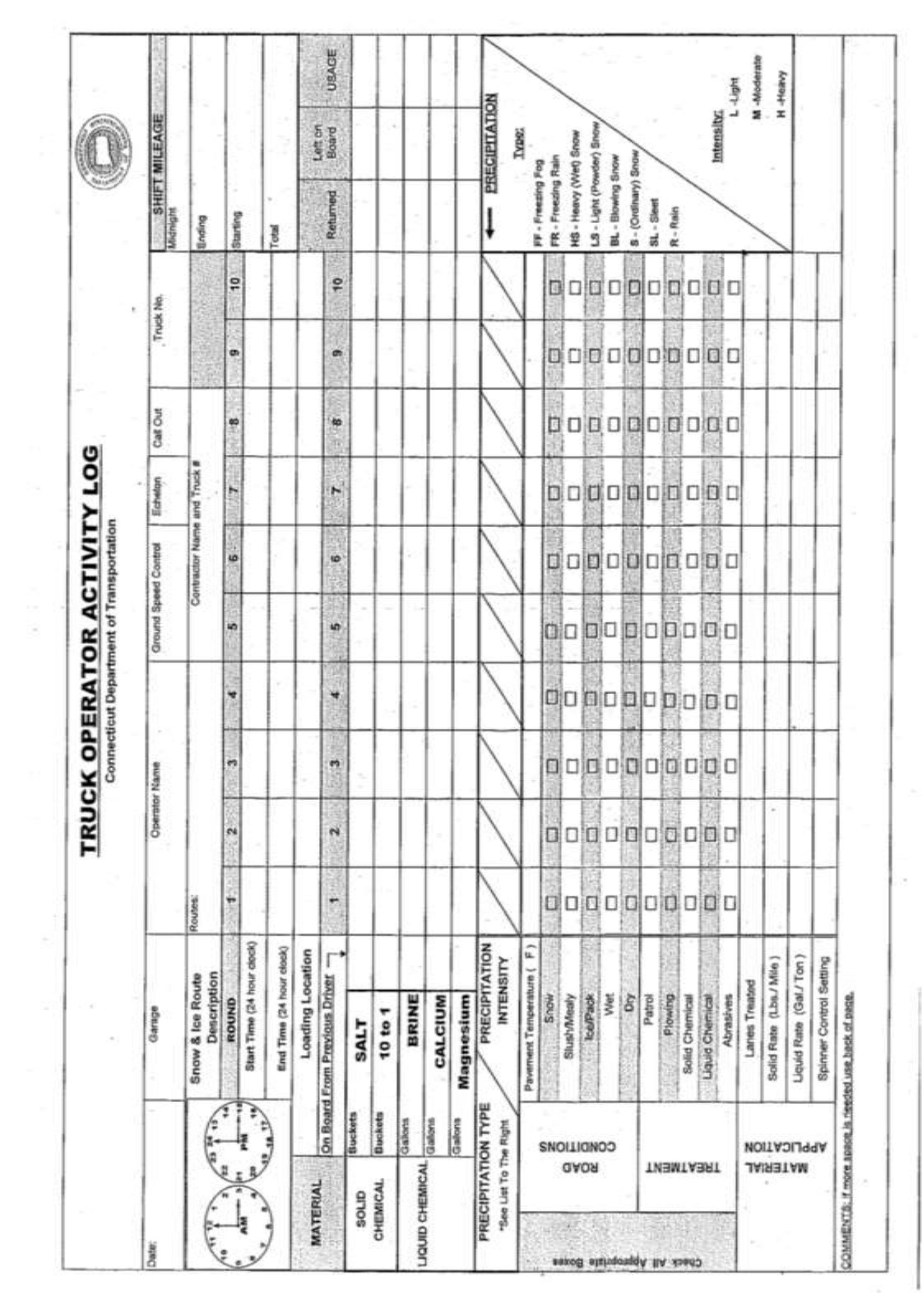
years 2007 – 2014 had less average snow than the period 2000 – 2006, but the Department used slightly more (15%) chlorides. In this case, "total snow" is an oversimplification for storm/winter characterization. Other factors, such as duration, ice accumulation, subfreezing temperatures when more chlorides are needed to be effective, and re-freezing events influence the severity of the winter and material needed.

As is common practice, all material spreaders are calibrated prior to the snow season and validated periodically by CTDOT Maintenance staff according to the procedures of the equipment manufacturer /4/. Figure 13 shows a material spreader calibration in-progress. Each truck is labelled with the calibration results as shown in Figure 14, for easy reference by different drivers and supervisors. Sodium chloride is purchased under contract and accepted according to: (1) Purity: as stated in AASHTO M—143-13 "Standard Specification for Sodium Chloride," (ASTM D—632-12, Type 1)/14/; (2) Gradation: requirements set forth by the Department; and, (3) Moisture Content: not to exceed 3% by weight. Salt testing for material quality occurs every 10 calendar days and is administered by the CTDOT's Material Testing Laboratory.



TRUCK OPERATOR ACTIVITY LOG

Connecticut Department of Transportation

Date:	Garage	Operator Name	Ground Speed Control	Echelon	Call Out	Truck No.	SHIFT MILEAGE
	Snow & Ice Route Description	Routes:		Contractor Name and Truck #			Midnight / Ending
	ROUND	1	2	3	4	5	6	7	8	9	10	Starting
	Start Time (24 hour clock)											
	End Time (24 hour clock)											Total

MATERIAL	Loading Location													
	On Board From Previous Driver	1	2	3	4	5	6	7	8	9	10	Returned	Left on Board	USAGE
SOLID CHEMICAL	Buckets SALT													
	Buckets 10 to 1													
LIQUID CHEMICAL	Gallons BRINE													
	Gallons CALCIUM													
	Gallons Magnesium													

PRECIPITATION TYPE *See List To The Right	PRECIPITATION INTENSITY	
	Pavement Temperature (F)	
ROAD CONDITIONS	Snow	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
	Slush/Mealy	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
	Ice/Pack	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
	Wet	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
	Dry	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
TREATMENT	Patrol	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
	Plowing	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
	Solid Chemical	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
	Liquid Chemical	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
	Abrasives	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
MATERIAL APPLICATION	Lanes Treated	
	Solid Rate (Lbs./Mile)	
	Liquid Rate (Gal./Ton)	
	Spinner Control Setting	

Check All Appropriate Boxes

← PRECIPITATION

Type:

FF - Freezing Fog
FR - Freezing Rain
HS - Heavy (Wet) Snow
LS - Light (Powder) Snow
BL - Blowing Snow
S - (Ordinary) Snow
SL - Sleet
R - Rain

Intensity:

L - Light
M - Moderate
H - Heavy

COMMENTS: If more space is needed use back of page.

Figure 12: Example of Truck Operator Activity Log

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Table 1: Example of Material Reports Generated After Each Storm, by Section
(Excerpt from Statewide Storm Summary Report)/13/

Snow & Ice Control Material Usage: 2012-2013 Season

Through Storm # S08

Section	Hours						Sand (Cubic Yards)					
	Storm Total	% of Bud.	Previous Total	Total to Date	Hours Budgeted	% Exp	Storm Total	% of Bud.	Previous Total	Total to Date	Amount Budgeted	% Exp
11	24.00	9.27	143.00	167.00	259.00	64.48	0.00	0.00	0.00	0.00	7,375.00	0.00
13	20.00	7.72	141.50	161.50	259.00	62.36	0.00	0.00	216.00	216.00	6,239.00	3.46
21	21.00	8.24	133.50	154.50	255.00	60.59	0.00	0.00	0.00	0.00	6,870.00	0.00
23	22.00	8.56	137.00	159.00	257.00	61.87	0.00	0.00	0.00	0.00	5,604.00	0.00
31	24.00	9.49	141.00	165.00	253.00	65.22	0.00	0.00	0.00	0.00	4,737.00	0.00
33	24.00	9.45	141.00	165.00	254.00	64.96	0.00	0.00	0.00	0.00	6,008.00	0.00
41	24.00	8.96	138.50	162.50	268.00	60.63	0.00	0.00	0.00	0.00	8,839.00	0.00
43	24.00	8.82	149.00	173.00	272.00	63.60	0.00	0.00	0.00	0.00	7,204.00	0.00
Section	**Salt (Tons)**						**Chloride (Gallons)**					
	Storm Total	% of Bud.	Previous Total	Total to Date	Amount Budgeted	% Exp	Storm Total	% of Bud.	Previous Total	Total to Date	Amount Budgeted	% Exp
11	1,739.88	7.13	9,505.51	11,245.39	24,389.00	46.11	12,185.00	10.18	58,634.00	70,819.00	119,741.00	59.14
13	1,868.40	6.88	8,401.89	10,270.29	27,155.00	37.82	16,385.00	12.20	64,935.00	81,320.00	134,311.00	60.55
21	1,962.31	10.47	7,864.63	9,826.93	18,746.00	52.42	20,702.00	20.83	68,204.00	88,906.00	99,382.00	89.46
23	1,828.44	11.04	7,059.67	8,888.11	16,566.00	53.65	21,145.00	21.89	64,505.00	85,650.00	96,578.00	88.68
31	1,069.20	6.52	7,651.98	8,721.18	16,409.00	53.15	9,364.00	12.49	43,619.00	52,983.00	74,946.00	70.69
33	1,669.68	8.90	6,114.61	7,784.29	18,754.00	41.51	13,008.00	16.81	40,224.00	53,232.00	77,391.00	68.78
41	1,775.52	7.07	7,856.86	9,632.38	25,125.00	38.34	15,179.00	15.19	50,998.00	66,177.00	99,936.00	66.22
43	1,926.56	8.61	8,989.43	10,915.99	22,373.00	48.79	16,159.00	16.46	66,255.00	82,414.00	98,144.00	83.97

Note: Column Title annotated to 'Chloride' (Gallons), refers to Magnesium Chloride Solution.

Table 2: Example of Material Report by Crew, (excerpt from Statewide Storm Summary Report) /13/

...Total Amounts...

Crew	10:1	Sand	Salt	Brine	CalC
111	0	0	220	0	810
112	0	0	269	0	2600
113	0	0	310	0	2700
114	0	0	338	0	2837
116	0	0	244	0	1052
117	0	0	230	0	2186
Total	0	0	1611	0	12185

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Table 3: Estimated Winter Storm and Material Use Totals, 2001 – 2014

Season (Years)	Storms (No.)	Activities (No.)**	Total Snowfall (Range, Inches) ***	Sand (Tons)	Sodium Chloride (Tons)	Calcium Chloride* (Tons)	Magnesium Chloride* (Tons)	Total Chlorides Applied (Tons)
2000/ 2001	17	11	25-71	307,310	140,850	-	-	140,850
2001/ 2002	9	5	5-26	94,260	40,220	-	-	40,220
2002/ 2003	16	10	50-98	303,110	140,110	-	-	140,110
2003/ 2004	12	9	46-79	225,310	103,820	-	-	103,820
2004/ 2005	18	4	51-77	317,130	161,900	-	-	161,900
2005/ 2006	11	6	25-62	198,310	107,930	-	-	107,930
2006/ 2007	9	6	6-30	6,790	104,760	481	-	105,241
2007/ 2008	14	10	13-70	2,860	185,000	1,240	-	186,240
2008/ 2009	13	8	33-58	4,230	179,710	1,492	-	181,202
2009/ 2010	12	5	22-67	60	131,040	1,333	-	132,373
2010/ 2011	15	5	52-87	10	179,490	1,092	748	181,330
2011/ 2012	6	4	9-31	-	62,550	141	422	63,113
2012/ 2013	11	9	35-74	-	160,930	-	1,727	162,657
2013/ 2014	17	11	40-62	-	225,170	-	2,341	227,511

Notes: Sand and sodium chloride values rounded to the nearest 10 ton.
Shaded area indicates seasons prior to deployment of anti-icing practices.
*Applied in Solution: $CaCl_2$ (32%) Solution,(3.54lbs/gal); $MgCl_2$ (30%) Solution,(3.23lbs/gal).
**Activities are precipitation events, do not include applications from 're-freeze' events.
***Snowfall amounts, as measured at CTDOT Maintenance Facilities.

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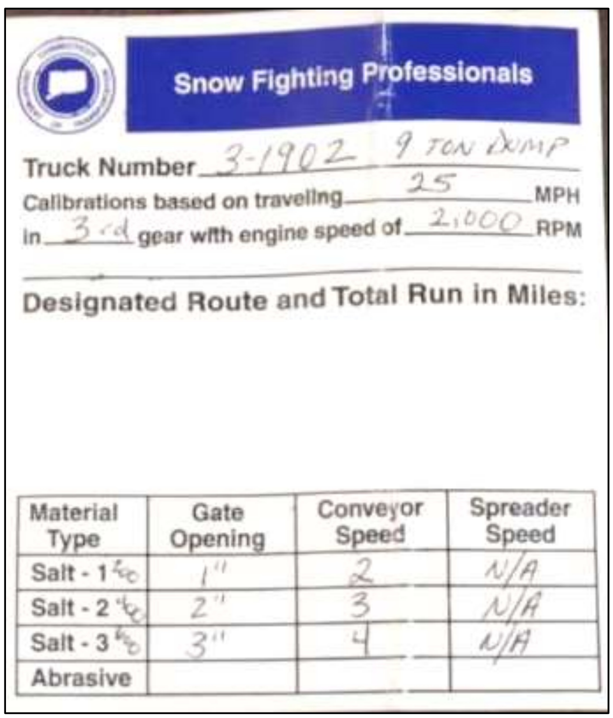
Figure 13: Spreader calibration



Snow Fighting Professionals

Truck Number 3-1902 9 TON DUMP

Calibrations based on traveling 25 MPH

in 3 rd gear with engine speed of 2,000 RPM

Designated Route and Total Run in Miles:

Material Type	Gate Opening	Conveyor Speed	Spreader Speed
Salt - 1 200	1"	2	N/A
Salt - 2 400	2"	3	N/A
Salt - 3 600	3"	4	N/A
Abrasive			

Figure 14: Calibration ticket, displayed in each vehicle

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During the Off-Season

During the off-season, work is done to facilitate the snow and ice operations for the next winter season. This includes:

- Equipment is cleaned and a neutralizing agent is applied.
- Snow plowing routes are reviewed annually for the purposes of optimization and efficiency:
- Potentially hazardous trees and brush are removed;
- Structures, drainage areas and other roadside obstacles are identified and staked before the next season.

Tree and branch (canopy) removal is critical to reduce the risks of falling trees and limbs, as well as accumulated snow and ice dropping from overhead canopy. Reduced canopy improves sun exposure to naturally aid in the snow and ice removal process/15/. As such, this also results in reducing the amount of materials needed to combat both storm and re-freezing events. Additionally, during the off-season stockpiles are replenished, equipment and supplies are replaced and contracts needed for the next winter's activities are executed.

Storm Characterization

Snow and ice events are designated and tallied as storms or activities. Storms and activities are categorized based on the duration, percent of workforce activation and distribution statewide. As such, activities are typically less than six hours with less than 50% of the workforce activated statewide, and storms are longer in duration with 50% or more of the snow and ice control workforce activated statewide. For planning purposes, CTDOT budgets for 12 storms per year based on past averages.

During the 2013/2014 season, the average storm was 20 hours. Figure 15 provides a graphical depiction of how the number of storms varies from year to year. As shown, these range between as many as 18 storms in the 2004/2005 season, and 17 in 2013/2014 season, to as few as six in the 1999/2000 and 2011/2012 seasons. State work-forces are also called to action when isolated weather conditions occur. These necessary actions, such as spot treatments in the case of possible "re-freeze," are not reflected in storm and activity tallies.

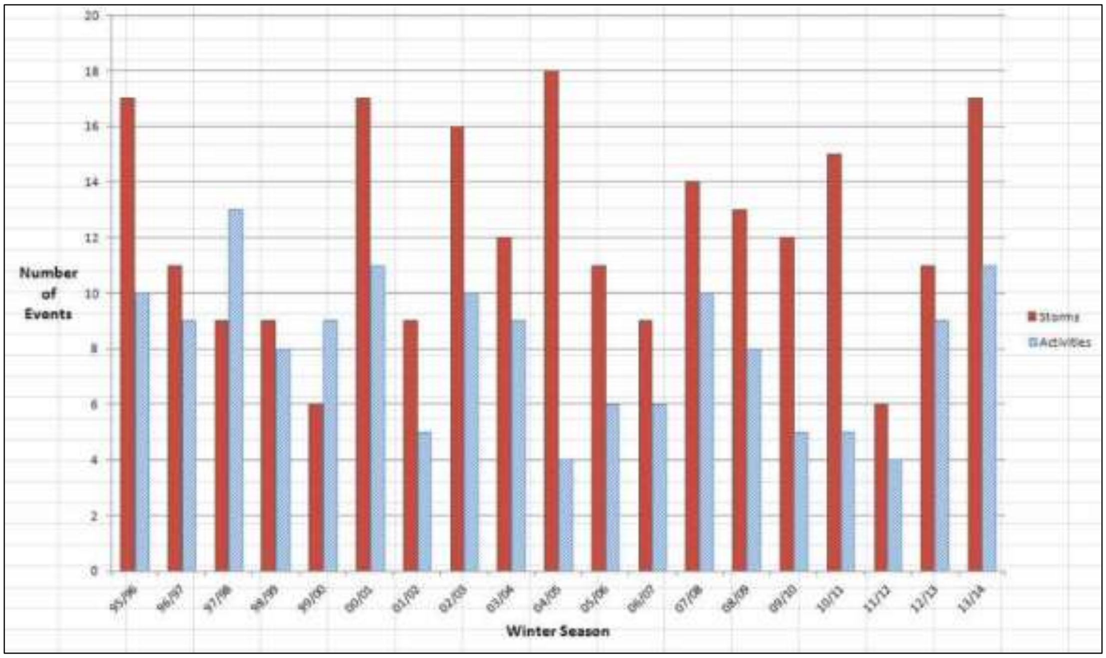

Figure 15: Number of Storms and Activities, by Winter Season (1996 – 2014)

A Decade of Advancements

"Agencies are continually seeking better ways to handle snow and ice problems"/7/. During the last decade there have been important improvements to snow and ice maintenance operations in Connecticut. These include adoption of anti-icing, pre-treating and pre-wetting practices and strategies, as well as advancements in equipment, data for decision-making and weather forecasting. Table 4 provides information on the progression of practices in a maturity chart format.

The change from deicing to anti-icing was described as "revolutionary" in a FHWA's Public Road article in 1995 entitled, "New Strategies Can Improve Winter Road Maintenance"/16/. Based on national field trials, significant input from other agencies, recommendations in the 2006 study entitled, "Improving Winter Highway Maintenance – Case Studies for Connecticut's Consideration"/18/, and recommendations from the 2005 NTSB Highway Accident Report, "Multiple Vehicle Collision on Interstate 95, Fairfield, CT January 17, 2003" /19/, CTDOT adopted improved approaches and technologies for winter highway maintenance, including anti-icing for the winter season 2006/2007. As described by FHWA in 1995, anti-icing is a "new strategy for preventing a strong bond from forming between snow or frost and the pavement surface"/16/. Advanced anti-icing methods represent a paradigm shift from traditional deicing methods. "Deicing is familiar to most agencies since it has been the most widely used strategy in the past"/16/. Traditional deicing methods allow snow to accumulate prior to removal and often resulted in "snow pack" that bonded to the road surface for hours and days, creating safety concerns. In the past, a sand and salt (sodium chloride) mixture (mixed at a ratio of 7:2) was spread behind the plows with the intent of improving vehicle traction to the snow pack. Numerous studies showed that abrasives (i.e., sand) have little friction-enhancing value on a road with any substantive level of traffic /17/. In addition to the limitations on effectiveness, use of sand required extensive cleanup, contributed to airborne particles and impacted the environment (example: water flow at streams)/15,17/. AASHTO and FHWA documented best practices indicate that sand should not be used for routine snow and ice operations/7, 6/. Hence, sand is only prescribed on Connecticut State highways during specific circumstances where ice or hilly terrain warrant remediation.

CTDOT began programming the pre-treating of select locations during the winter of 2006-2007 as part of the overall anti-icing strategies. Pre-treating had documented benefits by other states /6/ including:

- significantly reduces accidents on major river crossings;
- mitigates snow and ice from bonding to pavement;
- provides plow drivers more time at the onset of a storm;
- reduces salt use;
- promotes bare pavement sooner after storm; and,
- reduces overall cost of snow operation.

As indicated in Table 4, CTDOT also began "pre-wetting" in 2006. CTDOT opted for pre-wetting to improve the effectiveness of the salt being applied. It is a commonly used practice to improve salt activation, retention of the salt on the road by reducing the effects of bouncing, blowing and sliding of the salt, and this improved performance can result in an overall reduction in salt use /7,6/. The application rate was derived from a National Cooperative Highway Research Program (NCHRP) study 577,/20/, experience and the capabilities of the CTDOT fleet and equipment. Initially, a calcium chloride solution was used (2006 – 012), until availability of the material became problematic. For this reason, CTDOT began using a magnesium chloride solution for pre-wetting, beginning during the 2010 season, and changed to all magnesium chloride solution for pre-wetting in 2012. Correspondingly, facilities and equipment received the necessary upgrades to accommodate the new practices. Facilities were equipped with liquid chloride storage tanks and trucks with saddle-tanks for the purpose of pre-wetting. Since 2007, new fleet trucks are pre-equipped when purchased with larger tanks (125 gallon) integrated on the vehicle.

Weather technology advancements include the use of RWIS/21, 22/ and vehicle-mounted pavement (surface) temperature monitors. The improved temperature and field data enable improved application of anti-icing methods and storm management decision-making.

Table 4: CTDOT Snow and Ice Control Maturity Chart

Prior to 2006	2006 – 2013	2013-2014 Season and Beyond
Strategy : Deicing	**Strategy: Anti-Icing**	**Strategy: Anti-Icing**
• Sand & Sodium Chloride (7:2 Ratio) Rate: 1564 lbs./2-lane mile (LM), (non-multi-lane) • Sodium Chloride Rate: 432 lbs./2-LM	Sodium Chloride Rate: 200 lbs./LM	Sodium Chloride Rate: 200 lbs./LM
CT Patent on Brine Truck Technology; 1979	Programmed Pre-treating at Select Locations: Brine Solution (23% Sodium Chloride); 2007 – 2013	Programmed Pre-treating at Select Locations: Brine Solution (23% Sodium Chloride)
Pre-treating and Brine Application Field Trial; 1997 – 1998	Pre-Wetting: (All Pre-mixed, uninhibited, unless indicated.) • Inhibited Calcium Chloride Solution (32%); 2006 – 2008 • Calcium Chloride Solution (32%); 2008 – 2010 • Calcium Chloride (32%) or Magnesium Chloride Solution 30%); 2010 – 2012 • Magnesium Chloride Solution (30%); 2012 – 2013	Pre-Wetting : 1 gallon Magnesium Chloride Solution/LM; Magnesium Chloride Solution (30% by weight)
First Road Weather Information System (RWIS) installed, Route 2, Lebanon, CT; 1997	Additional RWIS Installed	RWIS Network • 13 Existing RWIS Systems • 23 Additional Proposed
Fleet: • Began installing air and temperature sensors on maintenance vehicles; 1999	Fleet/Facilities: • Acquired Trucks and updated facilities for pretreating; 2006 • Continued to deploy air/pavement temp sensors on vehicles • Trial Rear-Center Vehicle Salt Application Spreader; 2009-2013 • Developed CT Rear Truck-Mounted Discharge Chute; 2012 • Underbody scraper blades, 6 Trucks	Fleet/ Facilities: • Increased salt brine capabilities at various maintenance garages. • Purchased Vehicles Rear-Center Vehicle Salt Application Spreader for use on multi-lane highways • Purchased industrial snow blowers; 2013 • Composite blades • Trial of Salt-Slurry Generation Applicator; 2013 • Purchase of three Salt-Slurry Generators

The fleet, facility features and capabilities have continued to develop and evolve over time. Recent fleet advancements include methods of dispensing the salts, and snow-plowblade material (e.g. composites), designs (e.g., flexible blade systems), as well as addition of the “underbody scraper.” The underbody scraper is an attachment used for removal of snow pack in high volume urban areas. This attachment is mounted mid-truck. The Department added industrial snow blowers to its fleet after the Blizzard of 2013 to improve the rate and efficiency of accumulated snow removal. CTDOT is currently developing a linear reference system (LRS) for the Connecticut highway network. This system will provide the ability to spatially link routing and other roadway attribute data for road network management purposes. It is envisioned that this technology will be utilized for snowplow route optimization, as well as providing the opportunity for further advances in snow and ice operations.

Innovation, Pilots and Trials

CTDOT has explored new methods to improve practices and conducted field trials and pilot studies. Some of the most recent methods tested include use of a corrosion inhibitor (2006/2007); non-intrusive sensor technology for RWIS data collection in 2013, bridge rinsing in 2012, the CTDOT rear-mounted discharge chute (2012) and the salt-slurry generator (2013).

- Vehicle Surface Temperature Sensors

Surface pavement temperature sensors were initially installed on several vehicles in 2000. Use of these devices proved to be reliable and instrumental to decision-making. Widespread implementation was adopted, resulting in all supervisory vehicles and lead echelon plow trucks being equipped with both air and pavement surface temperature sensors.

- Pre-Wetting

For pre-wetting, a calcium chloride liquid anti-icing agent solution with corrosion inhibitor was used on the state highway network for the 2006/2007 and a portion of the 2007/2008 seasons. It was purchased pre-mixed. Problems were encountered with the bulk storage of the corrosion inhibited calcium chloride resulting from settlement and coagulation within the tanks and in the clogging of the application nozzles. These problems were attributed to the corrosion inhibitor. In addition, there were concerns regarding the impact to the environment, specifically, the detrimental impact to aquatic life by increasing the biochemical oxygen demand and degrading the overall water quality. Little evidence was available to support the product effectiveness. Use of this product was discontinued. An uninhibited calcium chloride solution was then used for pre-wetting during remainder of the 2007/2008 winter season. Storage and nozzle clogging were not issues with the uninhibited solution.

- Advanced RWIS Technologies

Recent advancements in RWIS employ non-intrusive sensor technologies. This type of RWIS is being used at one location, and is proposed for additional sites. Its initial use during the winter of 2013/2014 appears to provide reliable information, and provides the benefit of being independent of pavement condition and repairs. Other states report similar results/23/.

- Bridge Rinsing

A pilot program was conducted to rinse residue and debris from non-lead bridge structures not located over watercourses. Methods and protocols, based on those employed in other states, were developed in cooperation with the Department of Energy and Environmental Protection (DEEP) for pre-stressed concrete and lead-free multi-beam steel structures. Discussions were held with New England states through the AASHTO Northeast Bridge Preservation Partnership (NEBPP) (https://tsp2bridge.pavementpreservation.org/). The pilot consisted of the rinsing of 25 structures and was completed on June 5, 2012.

- CTDOT Rear-Mounted Discharge Chute

In winter 2012/2013, CTDOT District II Maintenance employees developed a rear truck-mounted discharge chute for improved application of salt onto the centerline of the roadway. Figure 16 shows this innovative device. This innovation was awarded the Connecticut Transportation Institute's Creative Solutions Award in 2013. These devices have been successfully installed on the CTDOT rear-gate vehicle fleet, when applicable.

Figure 16: The Connecticut Rear Truck-Mounted Discharge Chute

- Salt-Slurry Generator

During the winter of 2013/2014, a trial of a salt-slurry generator was conducted. The salt-slurry generator, shown in Figure 17, is a vehicle-mounted device that provides greater efficiency to the pre-wetting and salt application process. This is accomplished by reducing the gradation of the salt for quicker activation; and is a better method for infusion of the deicing liquid. In addition, it provides the ability for increased pre-wetting rates /24/. The trial was conducted on a plow route selected in

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proximity to the CTDOT headquarters for visual evaluation. Adjustments were conducted as needed for the operation. Initial indications, based on visual observations, are that the technology shows the potential for benefit. The Department currently has three of these units in operation. Work is being undertaken to determine and adjust spreader control parameters as well addressing mechanical and operational items. Additional field testing is ongoing.

Figure 17: Salt-Slurry Generator

Operational Coordination and Oversight

Before, during and after a storm there is considerable operational coordination and oversight. As part of this process, there are strategically planned meetings, post-storm critiques, to review the effectiveness of the snow and ice control. These include a meeting after the first storm, every other storm, special conditions and major storm events, as well as after the season. There are weekly status reports during the season. Items that are reviewed include: material usage, transactions and balances, road conditions, contractor results, equipment performance and weather reporting. "Tailgate talks" are routinely held at garages to communicate with plow operators and maintenance personnel regarding issues, storm critique and safety topics.

An informal Snow and Ice Control Committee was formed in 2006 in an effort to strategize and develop the transition protocol and training from a deicing to an anti-icing priority. This committee was formalized into a Departmental Standing Committee in 2015. Personnel from the Bureau of Highway Operations and Maintenance, with representatives from the Bureau of Policy and Planning, Environmental Planning Division, Office of Engineering and the Bureau of Finance and Administration serve on the Committee. This committee typically meets on a monthly basis to provide valuable input and review of the process, including discussion and critique of snow and ice-related issues and concerns, environmental policy and materials. As a Standing Committee, this committee will produce an annual report describing their activities, deliberations and information from assessing the state-of-the-practice.

Training, Outreach and Collaboration

The Department conducts training on snow and ice control. New and experienced workers comprising employees from CTDOT Maintenance, as well as other areas of CTDOT and DEEP, receive annual classroom and field instruction. Field training includes area and route-specific instructions in conjunction with the staking and marking activities for the upcoming season.

Educational programs and resources are provided to staff from municipal agencies through the Connecticut Technology Transfer Program (T^2), funded jointly by FHWA and CTDOT through UConn's Connecticut Transportation Institute (CTI). Numerous educational programs are provided by T^2 that are designed to address snow and ice operations. These include: a "Public Works Academy" for new municipal public works employees, with one day designated "Safe Operation of a committtt and Winter Operations," typically taught by CTDOT staff; The "Road Master Program," designed for participants from municipal agencies and CTDOT, that includes instruction on "Planning and Managing Snow and Ice Operations;" and the "Road Scholar Program," that includes roundtable discussions on the topic of winter operations for attendees from municipal and state agencies (CTDOT, DEEP, etc.). In addition, informal "Winter Operations Roundup(s)" are held periodically after the winter season to debrief while issues are fresh. Resources and outreach include technical and safety briefs, /25, 26/ as well as opportunities to be informed on practices through surveys (T^2 CT Winter Operational Survey, [2012]), demonstration of new techniques and equipment at T^2 Expos and T^2 Newsletter articles. In addition, T^2 provides a very successful "Public Works Online Forum" that is used routinely during storms to share information, request mutual aid, and as well as a mechanism for state agencies to disseminate information to the public works community.

CTDOT seeks opportunities to improve practice by having discussions with other state agencies. As part of this effort, Connecticut joined the FHWA Pooled Fund Project TPF-5(218), "Clear Roads Winter Highway Operations." This research program focuses on practical research for winter highway maintenance. It has 29 member states /26/. Extensive information is available on the project's website, www.ClearRoads.org.

CTDOT Office of Maintenance staff are actively engaged in seeking out information on best practices to employ in Connecticut through dialogue, webinars and literature /27/. Snow and ice operations are the focus of discussions at AASHTO meetings, as well as regional sessions. Connecticut has had ongoing dialogue with practitioners in New York State who have similar weather and challenges.

Integrated Operations

Improved snow and ice operations are achieved through coordinated efforts with other functional areas, agencies and organizations. CTDOT's operations centers, located in Newington and Bridgeport, monitor traffic and weather conditions 24/7 and support the storm room during severe winter weather. These monitoring operations include utilizing 324 available traffic cameras statewide, as well as communicating with the State Police on any weather-related incidents that occur and apprising the storm monitors and the operation managers. To facilitate mobility, traffic signal timing on specific routes is adapted to winter weather conditions to improve operations.

The referenced highway traffic cameras are available for public access and media use. The traffic camera images are routinely broadcast to the public as part of television news reports, where they are instrumental in providing the public visual condition information for travel decisions. CTDOT provides weather information on their website, in a section entitled, "Weather Round-up," (http://www.dotdata.ct.gov/WeatherRoundUp/WRU_Index.HTM). Information shared on the "Weather Round Up' is often used by towns and contractors for operations and is available for use by travelers for up-to-date information on temperatures, precipitation types and accumulations from around the state during winter weather events.

CTDOT is affiliated with TRANSCOM (Transportation Operations Coordinating Committee) (http://xcm.org) which is a coalition of 16 transportation and public safety agencies in the New York, New Jersey, and Connecticut metropolitan region. The aim of TRANSCOM is to update the coalition for the purpose of coordination with regard to accidents, road closures, traffic bans and any other traffic impacts related to storm or construction events. Through this program, conference calls are usually held throughout a specific event to get updates on road and public transportation conditions throughout the region. This facilitates the exchange of important information regarding cross-state road conditions for highway, transit and freight movement.

During extreme weather, the Governor may activate the State Emergency Operations Center (EOC) to conduct additional coordination with other state agencies. CTDOT will have staff representatives at the EOC during this time to address concerns as they arise. The Governor has the authority to declare travel bans.

Summary

CTDOT conducts snow and ice operations to keep the highway network reasonably safe and passable during winter weather events and to provide the best level of service within the limitations imposed by weather conditions; the availability of equipment, material and personnel; and environmental concerns. Snow and ice operations are essential for public safety, mobility and to minimize negative economic impacts. Advancements in technology and knowledge gained from operations and research have improved the state's winter maintenance practices. These include the anti-icing approach, pre-treating and pre-wetting methods, as well as new technologies for improved assessment of road conditions, material placement and fleet operations. CTDOT has adopted advancements and continues to actively seek improved practices to address the complex challenges of winter highway maintenance.

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APPENDIX D
QUESTIONS ASKED IN SURVEY OF CONNECTICUT MUNICIPALITIES

Thank you for taking time out of your busy schedule to complete this survey regarding salt usage in your agency, as well as your current practices. The survey is being conducted as part of a research study in conjunction with the Connecticut Academy of Science and Engineering.

This research study is in response to Public Act 14-199 that requires the Connecticut Department of Transportation to conduct an analysis of corrosion effects of chemical road treatments.

The results from this survey will not be published with your Municipality's name associated to the data, so it will not be possible to connect any specific practices with a particular Municipality.

The information from this survey will be used as part of the report to respond to the requirements of Public Act 14-199.

If you have at hand the salt and/or sand usage statistics for your Municipality for the winter seasons 2009-2010 through 2013-2014, the time to complete this survey should be under 15 minutes. If you need to gather information on salt and sand use quantities, we greatly appreciate your efforts in doing so. We realize that completing this survey is an additional task that consumes your valuable time, but we believe the information is quite important for optimizing use of resources for winter maintenance in Connecticut in the future.

Thank you in advance for your participation.

If you have any questions, please feel free to contact me:

Jim Mahoney
Connecticut Transportation Institute
University of Connecticut

james.mahoney@uconn.edu
860.486.9299

Please provide the following General Information

***1. Municipality Name**

***2. Name of Person Responding**

3. Title of Person Responding

***4. Email Address**

5. Telephone Number

***6. Number of Center Lane Miles Maintained in Your Municipality?**

Information about Quantities of De-Icing Chemicals Used During the Past 5 Years (Winter Seasons), Starting with 2009-2010, should be entered below.

7. Please enter the annual estimated tons of straight salt (sodium chloride) and solar salt used by your municipality for each of the five winter seasons indicated.

(There is a later question (Q8) about proprietary salt products such as, for example, Magic Salt and Clearlane. Please do not include those quantities here in Q7)

Tons of Salt Used 2009/2010

Tons of Salt Used 2010/2011

Tons of Salt Used 2011/2012

Tons of Salt Used 2012/2013

Tons of Salt Used 2013/2014

8. During any of the five Winter seasons indicated, did you use any proprietary, treated or alternative salt products? If so, could you please list them by season, and enter the approximate tonnage of each product used? If you used more than one proprietary product in a given year, please list all of them, including tonnage.

(Please be as specific as possible with the names as there are minor differences in the names some companies use, and yet it has a big impact on what is contained in the product)

Alternative Product(s) Used in 2009/2010

.......and Tons Used 2009/2010

Alternative Product(s) Used in 2010/2011

.......and Tons Used 2010/2011

Alternative Product(s) Used in 2011/2012

.......and Tons Used 2011/2012

Alternative Products(s) Used in 2012/2013

.......and Tons Used 2012/2013

Alternative Products(s) Used in 2013/2014

.......and Tons Used 2013/2014

9. In the five winter seasons indicated below, did you use any sand? If so, could you please indicate the approximate quantity of sand you used in tons, by year.

Tons of sand used 2009/2010

Tons of sand used 2010/2011

Tons of sand used 2011/2012

Tons of sand used 2012/2013

Tons of sand used 2013/2014

The next seven questions refer to newer or "innovative" techniques such as pre-treating, pre-wetting, and use of biodegradable non-chloride products, which might affect the amount of salt you use.

10. Do you pre-wet solid salt before you apply it to the roads? If yes, what is your application rate in gallons per-ton-of-solid-applied?

11. Do you pre-treat roadways with liquids before storms? If yes, what is your application rate in gallons per center-line mile?
Note: If you pre-treat with solid chemicals, that information is captured in a later question (Q12).

12. Do you pre-treat roadways with solids before storms? If yes, what is your application rate in pounds per center-line mile?

13. If you use a liquid or solid pre-treatment, please indicate where this is accomplished (for example, bridges treated only, intersections only, hills and trouble spots only, selected roads, or entire road network)

- ☐ Bridges pre-treated
- ☐ Intersections pre-treated
- ☐ Hills and trouble-spots pre-treated
- ☐ Selected routes pre-treated
- ☐ Entire road network pre-treated
- ☐ Other

14. If you selected "Other" for question 13, please explain here; otherwise skip to question 15.

15. If you pre-treat (i.e., answered questions 11 or 12), please describe below when and how you apply the pretreatment materials.

16. Do you use non-chloride biodegradable liquid by-products? If yes, what products have you used?

(Biodegradable by-products may include beet juice, molasses, corn derivatives, etc.)

17. If there are any other innovative techniques that you utilize that you care to share information about, please do.

You are almost done with the survey. The final six questions refer to equipment and winter maintenance procedures. And you are then welcome to provide any additional comments to us.

18. Have you noticed an increase in the corrosion rate of your plowing/chemical spreading equipment over the past five years? Please rate on a scale of 0 to 10 for severity.

(0 being no noticeable increase, 5 being a moderate increase, up to 10 being a major increase in corrosion).

☐ 0 ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 ☐ 6 ☐ 7 ☐ 8 ☐ 9 ☐ 10

19. What is the approximate average age of your winter maintenance plowing/chemical spreading equipment fleet?

Age in Years

20. What is your anticipated average service life for winter plowing/chemical spreading maintenance equipment, in years?

○ 5 years ○ 6 years ○ 7 years ○ 8 years ○ 9 years ○ 10 years ○ 15 years ○ 20 years ○ Other

21. How often do calibrate your salt spreading equipment?

22. Do you use ground speed control to spread chemicals?

○ Yes

○ No

23. Approximately what percentage of your fleet equipment contains ground surface temperature sensors?

Percent

24. Any other comments about winter maintenance or this survey are welcome here.

You are finished. THANK YOU for participating in this survey!

APPENDIX E
ADVANTAGES AND DISADVANTAGES OF DEICERS

Deicer Type	Advantages	Disadvantages
Abrasives	• Provides traction on ice • Provides color delineation for travel lanes for public assurance that a product has been applied to the road surface • Use is independent of temperature	• Does not lower freezing/melting point of ice (However, dark color of abrasive may help accelerate ice melting with sunshine) • Traffic causes migration of abrasives from roadways into ditches off roadways • Can increase water turbidity and be detrimental to the surrounding environment • Clogs drainage systems and accumulates in runoff areas, including streams and ponds • Can increase air pollution • Clumps together and freezes when damp, unless mixed with deicers • Absorbs and impedes effectiveness of deicers • Causes buildup on road shoulder areas precluding sheetflow runoff often requiring additional road maintenance • Material must be removed in the spring and summer at significant cost, both time and expense
Sodium Chloride	• Least expensive deicer for Connecticut and most states • Most prevalent deicer product (i.e., widespread availability) • Causes less deterioration of Portland Cement Concrete compared to other chlorides [21] • Can be used for anti-icing, deicing and pre-wetting • Not as hygroscopic (moisture absorbing) as other chlorides at moderate levels of relative humidity(which is beneficial for storage of solid form, and for pretreating roads with brine)	• Detrimental to surrounding environment (particularly for degradation of water quality in surface and groundwater, build up in soil and negative effects on some types of roadside vegetation from surface runoff, aerosols from vehicle spray, and wind) • Not very effective as a deicer when ambient temperatures are below 15°F, unless large quantities are used • Accelerates corrosion of metals including steel reinforcement in pavements and bridge structures • Corrosive to some motor vehicle components • Attracts animals to roadsides, which can be a safety hazard to motorists and animals • Can raise sodium levels in drinking water, adversely affecting human health

Deicer Type	Advantages	Disadvantages
Magnesium Chloride	• Lowers the freezing/melting point of water to approximately 5°F • Even at low temperatures solid magnesium chloride works quickly due to its ability to absorb moisture from the atmosphere (hygroscopic nature) • Can be used for anti-icing, deicing and pre-wetting	• Causes corrosion of metals including steel reinforcement in pavements and bridge structures • Corrosive to some motor vehicle components • Can accelerate corrosion (compared to sodium chloride) due to moisture absorption (magnesium chloride absorbs moisture from the atmosphere when relative humidity is as low as 30%, [22] which keeps surfaces on which it has adhered to wet) • Moisture attraction can make a pavement wet and potentially slick when the magnesium chloride is at a high enough concentration such as when it is used for anti-icing (pre-treating) • Magnesium ions can cause more severe concrete deterioration than sodium chloride [21] • In solid form, straight magnesium chloride is considerably more expensive than sodium chloride (> $150/ton)
Calcium Chloride	• Works effectively to lower the freezing/melting point of water to at least 25°F below that of sodium chloride and water • Works quickly due to its hygroscopic nature • Can be used for deicing, as brine for pre-wetting or anti-icing • Releases heat (exothermic) when applied as a solid and combines with moisture	• The calcium in calcium chloride can react with other elements in concrete and cause deterioration of the concrete • Can cause corrosion of metals in reinforced concrete for roads and bridges • Corrosive to some motor vehicle components • Considerably more expensive than sodium chloride (> $160/ton) • Its ability to attract moisture can make a pavement wet and potentially slick when present in high concentrations such as when it is used in anti-icing pretreatments • It is so hygroscopic that as a solid it eventually dissolves in the water it absorbs; this property is called deliquescence. To prevent this it must be kept in tightly-sealed containers
CMA	• Low toxicity to plants • Biodegradable • Main ingredient, dolomitic lime is abundant throughout the United States • Does not cause corrosion to most metals • Low toxicity to fish • Assists in prevention of surface water re-freezing • Reduces snow crystal tendency to stick together	• Only effective above 20° F • Can potentially lower dissolved oxygen concentrations in soils and receiving waters,[24] • Cost is at least 20 times that of sodium chloride (> $1,500/ton) [10] • Uses large quantities of energy in its production process (i.e., greater life cycle cost) • Due to lower density and greater quantity required to be effective, CMA requires more storage space than chlorides [23] • Requires a higher application rate than salts • Can cause deterioration of concrete due to calcium's chemical reaction with cement • Does not ionize as readily as sodium chloride, slowing initial reaction time, and therefore, is less successful than sodium chloride in melting snow and ice accumulations (particularly fluffy, dry snow)

Deicer Type	Advantages	Disadvantages
Sodium Acetate	• Exothermic (i.e., gives off heat when reacting with water) and therefore, helps prevent melted snow from re-freezing • Non-toxic (used in food and medical products) • Biodegradable • Generally non-corrosive to vehicles, bridges and utilities, which is especially critical for use in connection with aircraft operations and electronic runway lighting • Lowers the freezing point of water to 0°F	• Much more expensive than sodium chloride (>$ 1,900/ton) • May cause eye or skin irritation in solid form • Inhalation of dust during handling may cause respiratory tract irritation and coughing • May be corrosive to galvanized steel, zinc and brass • Quantities could become limited if selected for wider use such as on roadways • Decomposition can reduce dissolved oxygen in bodies of water
Potassium Acetate	• Low toxicity to fish, mammals and vegetation • Biodegradable • Biodegrades at low temperatures, and thus produces relatively low increase in BOD during spring thaw when temperatures rise • Generally non-corrosive to vehicles, bridges and utilities • Melts snow and ice twice as fast as sodium chloride at 20°F [3] and unlike most chlorides is active below zero degrees • Lowers the freezing point of water to -75°F at specific concentrations • Meets FAA approved specifications	• Corrosive to stainless steel • Expensive compared to sodium chloride ($2,000/ton; $5.50/gallon at 50% concentration) • May cause gel-like precipitate when mixed with sodium chloride for pre-wetting [20] • Decomposition can reduce dissolved oxygen in bodies of water • Dry compound is combustible so it is typically sold in liquid form for highway uses
Sodium Formate	• Relatively non-toxic • Similar deicing characteristics to sodium chloride	• Very limited usage experience in the United States — possibly at some airports • Data pertaining to a sodium acetate /sodium formate-based deicer suggests that during the spring thaw runoff, short periods of oxygen depletion in receiving waters may occur, with potential danger in warmer weather (Bang and Johnston, 1998) [30]
Potassium Formate	• Makes snow softer and less sticky • May be less detrimental to the environment than sodium chloride	• May be corrosive to electrical connectors • Not used very extensively in the United States • Limited information is available about this deicer • Decomposition can reduce dissolved oxygen in bodies of water

Deicer Type	Advantages	Disadvantages
Carbohydrates / Agricultural or Organic Byproducts	• Enhances performance of other deicers when mixed with them, thus, allows for potentially less deicer use per mile, which can reduce the amount of chlorides released into the environment • Helps sodium chloride "stick" to the road, (i.e., less bounce and scatter) • Dark color assists melting when in sunlight • Dark color provides for color delineation of travel lanes during snowy conditions	• Sticky when handling and applying • Expensive • Does not have significant ice melting capacity when used alone • The organic contents of byproducts when broken down may cause temporary anaerobic soil conditions as well as oxygen depletion in surface waters • Stickiness could cause chlorides (such as sodium chloride and magnesium chloride) to adhere to metals for longer periods of time.
Urea	• Non-corrosive to steel reinforcement • Fertilizes plants	• Is not very effective as a deicer below 25°F • Can cause sinus respiratory and eye irritation • Corrosive to some metals • Can burn (damage) vegetation in high quantities • Urea, by itself, has a high BOD and decreases the available oxygen to aquatic organisms • Costs approximately 500% as much as sodium chloride
Propylene Glycol	• Non-toxic • Biodegradable • Non-corrosive to metals • Works at very low temperatures • Safe for handling	• Expensive • Depletes oxygen in waters which can adversely affect aquatic life
Treated Road Salt (Proprietary)	• Performance at low temperatures (due to presence of magnesium chloride) • 70% less corrosive to steel (per PNS test as stated by manufacturers) than plain sodium chloride (due to the inclusion of corrosion inhibitors) • Less bounce and scatter (due to presence of water and biodegradable additives) • Potential lower total use of sodium chloride as a result of faster and lower temperature melting capabilities	• Degradation of Portland Cement Concrete (PCC) is possible in the presence of magnesium chloride (Magnesium ions cause more severe concrete deterioration than other constituents of common deicing chemicals) [2] • Detrimental to surrounding environment (particularly for degradation of water quality in surface and groundwater, build up in soil and negative effects on roadside vegetation from surface runoff, aerosols from vehicle spray, and wind) due to presence of sodium chloride • Products containing sodium chloride attract animals to roadsides, which can be a safety hazard to motorists • Products containing sodium chloride, can raise sodium levels in drinking water, adversely affecting human health

APPENDIX F
PACIFIC NORTHWEST SNOW FIGHTERS QUALIFIED PRODUCT LIST – PRODUCTS

Pacific Northwest Snow Fighters (PNS) Qualified Product List - PRODUCTS
Date of Listing: November 24, 2014

Category 1 - Corrosion Inhibited Liquid Magnesium Chloride

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Iceban 200*	Earth Friendly Chem.	8.4	26%	8/15/2002
Caliber M1000 AP	Envirotech Services Inc.	20.8	28%	8/2/2004
Meltdown with Shield AP	Envirotech Services Inc.	25.9	30%	8/2/2004
Hydro-Melt Green	Cargill	24.3	28.5%	8/1/2005
Meltdown APEX with Shield AP	Envirotech Services Inc.	25.1	30%	1/25/2006
FreezGard CI Plus	North American Salt	12.2	30%	8/28/2006
Ice B'Gone II HF	Sears Ecological Appl.	28.6	25%	8/9/2007
FreezGard LITE CI Plus	North American Salt	12.3	27%	6/13/2011
HydroMelt Liquid Deicer	Cargill	28	28.6%	8/15/2011
FreezGard CI Plus Sub Zero	North American Salt	14.1	27.5%	10/11/2011
Ice Ban 305	GMCO Corporation	25.3	26.6%	1/10/2013
FreezGard 0 CCI	GMCO Corporation	21.2	30.0%	1/10/2013
Meltdown Apex	Envirotech Services Inc.	22.4	30.0%	4/16/2014
Meltdown Inhibited	Envirotech Services Inc.	24.1	30.0%	4/29/2014

Note-Iceban 200 was formerly Iceban Performance Plus M
Those products marked with an asterisk (*) indicates that the stratification can be seen and agitation is required.

Category 2 - Corrosion Inhibited Liquid Calcium Chloride

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Liquid Dow Armor	Dow Chemical	26	30%	6/25/1999
Winter Thaw DI	Tetra Technologies	16.5	32%	9/13/1999
Corguard TG	Tiger Calcium Services	27.7	29%	1/9/2001
Road Guard Plus	Tiger Calcium Services	16	25%	6/5/2006
Calcium Chloride with Boost (CCB)	America West	18.4	32%	4/10/2014

Category 3 - Non Corrosion Inhibited Liquid Calcium Magnesium Acetate

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Liquid CMA 25%	Cryotech	-11	25%	5/19/1998
SC CMA 25%	Sure Crop Farm Services	-2.8	25%	9/13/1999

1

Category 4 - Corrosion Inhibited Solid Sodium Chloride

Category 4A- Corrosion Inhibited Solid Sodium Chloride (Corrosion Percent Effectiveness of 30% or less)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Inhibited Ice Slicer	Envirotech	30	N/A	5/19/1998
CG-90 Non-Phosphate 2.8%	Cargill	27	N/A	5/19/1998
IMC CI SALT A 3.5	North American Salt	28	N/A	8/21/2001
IMC CI SALT B 4.5	North American Salt	18.6	N/A	8/21/2001
Clear Lane PNS Enhanced Deicer	Cargill	28.9	N/A	8/1/2005
Ice Slicer Elite	Envirotech	16	N/A	8/1/2005

Category 4B- Corrosion Inhibited Solid Sodium Chloride (Corrosion Percent Effectiveness 31% to 85%)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Ice Slicer RS	Redmond	80	N/A	10/13/2009
Ice Slicer Super Blend Plus	Redmond	60.4	N/A	10/13/2009

Category 5 - Corrosion Inhibited Sodium Chloride Plus 10% Magnesium Chloride (Solid)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
CG-90 Surface Saver 10%	Cargill	15	N/A	5/19/1998
Meltdown 10	Envirotech	30	N/A	5/19/1998
Surface Saver PNS 10%	Cargill	27.2	N/A	8/21/2001

Category 6 - Corrosion Inhibited Sodium Chloride Plus 20% Magnesium Chloride (Solid)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
CG-90 Surface Saver 22%	Cargill	26	N/A	5/19/1998
Meltdown 20	Envirotech	27	N/A	8/8/2000
Surface Saver PNS 20%	Cargill	22	N/A	8/21/2001

Category 7 - Calcium Magnesium Acetate (Solid)

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
CMA	Cryotech	-7	96%	5/19/1998

Category 8 - Non Corrosion Inhibited Solid Sodium Chloride

CATEGORY 8A-B Standard Gradation, Brining Salt, Insoluble Material less than 1%, and Moisture less than 0.5%.

Product Name	Manufacturer			Date Approved
DriRox Coarse Salt*	North American Salt			9/21/2012
Bulk Coarse Solar	Morton Salt			4/21/2006
Intrepid Coarse Salt	Intrepid Potash			6/3/2010

* Product was renamed from NASC Salt (Coarse). The product has been approved since 8/2000.

CATEGORY 8A-R Standard Gradation, Road Salt, Insoluble Material less than 10%, and Moisture less than 0.5%.

Product Name	Manufacturer			Date Approved
Cargill Dry Salt	Cargill			6/1/1998
Mineral Melt	NSC Minerals			6/1/1998
DriRox Coarse Salt*	North American Salt			9/21/2012
Kayway Salt (Coarse)	Kayway Industries			12/23/2003
Bulk Coarse Solar	Morton Salt			4/26/2005
Ice Slicer Super Blend	Redmond Mineral			8/2/2006
ISCO Bulk Rock Salt	K+S			6/23/2008
Natural Alternative Ice Melt	NaturaLawn of America			5/17/2010
Intrepid Coarse Salt	Intrepid Potash			6/3/2010

* Product was renamed from NASC Salt (Coarse). The product has been approved since 8/2000.

CATEGORY 8B - Insoluble Material less than 10%, and Moisture less than 5.0%.

Product Name	Manufacturer		%Moisture	Date Approved
Ice Slicer RS	Redmond Mineral		1.95	2/9/2003
QwikSalt	North American Salt		2.54	6/30/2004
Type C Treated Salt	Broken Arrow		2.94	8/2/2004
SS-5.0	Shelton's Salt		0.90	9/16/2004
Bulk Type C Road Salt	Morton Salt		2.63	4/26/2005
ESSA Salt	ESSA		0.84	6/26/2007
Rapid Thaw	Broken Arrow		2.49	3/4/2009
Bulk Deicing Salt	Central Salt		2.39	6/24/2013

CATEGORY 8C-B Fine Gradation, Brining Salt, Insoluble Material less than 1%, and Moisture less than 0.5%.

Product Name	Manufacturer			Date Approved
Mineral Melt	NSC Minerals			3/1/2006
Quick Brine RF	NSC Minerals			3/1/2006
Rocanville Standard Road Salt	NSC Minerals			10/6/2006
Medium Solar Salt	North American Salt			8/12/2009
Mixing Solar Salt	North American Salt			8/12/2009
Intrepid Medium Salt	Intrepid Potash			6/3/2010

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CATEGORY 8C-R, Fine Gradation, Road Salt, Insoluble Material less than 10% and Moisture less than 0.5%.

Product Name	Manufacturer			Date Approved
Mineral Melt	NSC Minerals			3/1/2006
Quick Brine VS	NSC Minerals			3/1/2006
Quick Brine RF	NSC Minerals			3/1/2006
Rocanville Standard Road Salt	NSC Minerals			10/6/2006
Medium Solar Salt	North American Salt			8/12/2009
Mixing Solar Salt	North American Salt			8/12/2009
Intrepid Medium Salt	Intrepid Potash			6/3/2010
Ice Slicer Near Zero	Redmond Minerals			12/3/2010

Category 9 - Corrosion Inhibited Liquid Sodium Chloride

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Salt Brine + Brine CI	Cargill	25.4	23.3	8/12/2009
Brine with Headwaters Inhibitor	Rivertop Renewables	25.6	22.5	11/24/2014
Brine with Headwaters 10F Inhibitor	Rivertop Renewables	26.7	22.4	11/24/2014

Category 10 - Corrosion Inhibited Liquid Sodium Chloride Plus Calcium Chloride

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
TC Econo*	Tiger Calcium Services	20.5	20/2 (1)	8/12/2009
Beet Heet Severe	K-Tech Specialty Coatings	21.1	15.3/5.4 (2)	7/13/2011
ESB	America West	21.0	18.8/2.3 (3)	4/14/2014
SO-CAL	Custom Spray Services	27.8	20.8/2.5 (4)	4/14/2014

1 - 20% NaCl and 2% $CaCl_2$
2 - 15.3% NaCl and 5.4% $CaCl_2$
3- 18.8% NaCl and 2.3% $CaCl_2$
4 - 20.8% NaCl and 2.5% $CaCl_2$

Category 11 - Corrosion Inhibited Liquid Chloride Blended Brines

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
Road Guard Plus*	Tiger Calcium Services	16	27 (1)	8/12/2009
Road Guard TC	Tiger Calcium Services	21.3	32.1 (2)	8/12/2009
Road Guard XCEL	Tiger Calcium Services	20.3	33.2 (3)	8/12/2009
IB 7/93-Thermapoint	Millennium Roads	24	26.7 (4)	5/1/2013

1 - 25% Calcium Chloride and 2% Magnesium Chloride
1 - 27.3% Calcium Chloride and 4.8% Magnesium Chloride
2 - 28.5% Calcium Chloride and 4.7% Magnesium Chloride
4 - 17.8% Calcium Chloride, 5.4% Sodium Chloride, and 3.5% Magnesium Chloride
Those products marked with an asterisk (*) indicates that the stratification can be seen and agitation is required.

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PNS Experimental Category - Approved Liquid Corrosion Inhibited Products

Product Name	Manufacturer	Corrosion Rate % Effectiveness	% Concentration	Date Approved
CF-7	Cryotech	0.0	50(1)	6/20/2001
CMAK	Cryotech	0.0	12.5/25(2)	6/20/2001
NC 3000	Glacial Technologies	-3.5	25(3)	3/13/2002
Alpine Ice-Melt	Nachurs Alpine Sol. Ind.	-4.8	50(4)	6/23/2008
Fusion 60/40	Eco Solutions	22.1	15.0(5)	11/23/2009
Beet Heet Concentrate***	K-Tech	14.8	21.7(6)	9/26/2012
AquaSalina+	Nature's Own Source	26.4	22.5(7)	9/19/2013
Isoway	Omex Environmental	-5.1	25.0(8)	4/15/2014
Geomelt S7	SNI Solutions	25.9	18.1(9)	4/17/2014
SOS AP***	Envirotech Services	21.0	26.0(10)	4/18/2014
SOS Inhibited***	Envirotech Services	25.3	26.0(11)	8/28/2014
AQ+IceBite Liquid Brine Deicer	Nature's Own Source	11.4	20.4(12)	8/28/2014
Ecolution Liquid Deicer	State Industrial Products	26.5	24.6(13)	8/28/2014
Ice Bite S	Road Solutions Inc.	15.0	22.1(14)	10/21/2014
XO-Melt$_2$	K-Tech	22.9	24.5(15)	11/3/2014
Husker Plus***	Smith Fertilizer and Grain	10.2	36(16)	11/24/2014

1 - 50% Potassium Acetate
2 - 12.5% Calcium Magnesium Acetate and 25% Potassium Acetate
3 - The product contains a 25% Potassium Acetate concentration. The product also contains 30% Carbohydrate material which is still under consideration as an active ingredient but at this time has not be included.
4 - 50% Potassium Acetate
5 - 15.0% Sodium Chloride, blend of 60% Fusion/ 40% Salt Brine
6 - Total Chloride Salt Blend with $CaCl_2$-11.9%, $MgCL_2$- 3.4%, KCL-2.7%, NaCl-3.7% . Carbohydrate content-28.8%. ***Material approved as a pre-wet material to solid salt. Not for direct application as a liquid deicer.
7 - Total Chloride Salt Blend with $CaCl_2$-9.0%, $MgCL_2$- 2.5%, and NaCl-11.0% .
8 - 25% Potassium Acetate
9 - 18.1% Sodium Chloride, blend of 30% Geomelt 55/ 70% Salt Brine.
10 - 26.0% $MgCl_2$ with a thicking additive. ***Material approved as a pre-wet material to solid salt. Not for direct applications as a liquid deicer.
11 - 26.0% $MgCl_2$ with a thicking additive. ***Material approved as a pre-wet material to solid salt. Not for direct applications as a liquid deicer.
12 - Total Chloride Salt Blend with NaCL-13.0% and $CaCl_2$-7.4%, blended with 15% IceBite.
13 - Total Chloride Salt Blend with $CaCl_2$-9.8%, $MgCL_2$- 2.3%, and NaCl-12.5% .
14 - 22.1% Sodium Chloride.
15 - Total Chloride Salt Blend with CaCl2-12.3%, MgCL2- 2.1%, and NaCl-10.1% .
16 - 36% Mixed Matrix Organic Salt Compounds derived from Sugar. ***Material approved as a pre-wet material to solid salt. Not for direct application as a liquid deicer.

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Pacific Northwest Snow Fighters (PNS) Qualified Product List - INHIBITORS
Date of Listing: July 18, 2014

Category A1 - Corrosion Inhibitor for Sodium Chloride Brine (Minimum 21% NaCl)

Product Name	Manufacturer	% NaCl		% Additive	Class	% Effectiveness	Date Approved
ArctiClear CI Plus	North American Salt	21.2		5	1	21.3	12/3/2010
Headwaters Corrosion Inhibitor	Rivertop Renewables	22.5		3.5	1	24.9	4/15/2014
Shield GLT Plus	Paradigm Chemical	22.6		5	1	28.7	4/15/2014
Headwaters 10F Corrosion Inhibitor	Rivertop Renewables	22.4		4.5	1	26.7	7/18/2014

Category A2 - Corrosion Inhibitor for Sodium Chloride and Calcium Chloride Brine (Minimum 15% NaCl & 2% $CaCl_2$)

Product Name	Manufacturer	% NaCl	% $CaCl_2$	% Additive	Type/Class	% Effectiveness	Date Approved
Boost SB	America West	18.8	2.3	20	I / 2	21.0	4/14/2014

Category A3 - Corrosion Inhibitor for Sodium Chloride (Minimum 15% NaCl)

Product Name	Manufacturer	% NaCl		% Additive	Class	% Effectiveness	Date Approved
ArtiClear Gold	North American Salt	18.8		15	2	26.6	12/3/2010
Beet 55 Concentrate	Smith Fertilizer & Grain	17.2		35	2	23.1	9/19/2013
Geomelt 55	SNI Solutions	18.1		30	2	25.9	4/17/2014

APPENDIX G

SUMMARY OF LABORATORY STUDY LITERATURE FOR DEICER CHEMICALS AND PORTLAND CEMENT CONCRETE

Lab Study (reference) Location	*Test Type*	*Description of Test Performed*	*Official Test Method(s)*	*Specimens Used*	*Solutions Used (and Explanation)*	*Study Results*
Peterson [95] Sweden	Soak	Immerse in 29 liters of solution **at 41**°F for 22 to 32 months (checked each month)	Not cited	**48 mortar prisms** **0.8 in x 0.8 in x 11 in** length change 24 at w/c 0.45 and 24 at w/c 0.60 Air content not given	• 25.9% NaCl • 42.7% $CaCl_2$ • 30.7% CMA • 26.7% Calcium Acetate	*Primary study objective was to test CMA in non-freeze soak* *Tests:* • Length change (monthly) • Mass change (monthly) • pH (monthly) • flexural strength (at end of study) • compressive strength (at end of study) Results: **calcium chloride solution**. Solutions with very low and very high concentration do not attack the concrete, but solutions with an intermediate concentration may destroy the concrete by strong expansion within a few days. Note, a calcium chloride solution on a concrete surface will constantly change concentration due to relative humidity. **CMA**: The attack of the CMA product according to our sample was so severe that this product should not be used for deicing of bridges and concrete roads. An essential condition for this attack is, however, that the temperature of the solution has the opportunity to rise well above the freezing temperature.
	Soak	Immerse in 29 liters of solution **at 68**°F for 22 to 32 months (checked each month)	Not Cited	**48 mortar prisms** **1.6 in x 1.6 in x 6.3 in** Mass and strength change 24 at w/c 0.45 and 24 at w/c 0.60 Air content not given	• 25.9% NaCl • 42.7% $CaCl_2$ • 30.7% CMA • 26.7% Calcium Acetate	
Cody et al 1996 [96] Iowa State University	Soak	Immerse in 100 ml solutions at 140°F for 222 days; test cycle observations performed every 132 hrs (5.5 days)	Not Cited	*All Iowa highway cores contained dolomite aggregate from the Silurian Hopkinton Formation or the Ordovician Galena Formation* (air content not given) • Rectangular **blocks 0.5 in. x 0.5 in. x 1 in.** cut from **High** durability **PCC cores** from in-service highways • Rectangular **blocks 0.5 in. x 0.5 in. x 1 in**. cut from **Low** durability **PCC cores** from in-service highways	• 17.6% NaCl = 3 M • 33.3% $CaCl_2$ = 3 M • 28.6% $MgCl_2$ = 3 M • Distilled Water • Magnesium Acetate • Magnesium Nitrate	The experiments document that the substitution of magnesium and/or calcium deicers for rock salt may have unintended consequences in accelerating concrete deterioration. Long-term, carefully controlled field experiments with magnesium and calcium deicers are essential in order to fully determine the effects of long-term use of these deicers under highway conditions and to determine if they are suitable substitutes for rock salt.

Continued **Cody et al 1996 [96] Iowa State University**	W/D	• Wet at 140°F; dry at 194°F; 4 cycles (each complete test cycle = 6.5 days) • Wet at 140°F; dry at 140°F; 6 cycles		• Rectangular blocks **0.5 in. x 0.5 in. x 1 in.** cut from **High** durability PCC cores from in-service highways • Rectangular blocks **0.5 in. x 0.5 in. x 1 in.** cut from **Low** durability PCC cores from in-service highways	• 17.6% NaCl = 3 M • 33.3% $CaCl_2$ = 3 M • 28.6% $MgCl_2$ = 3 M • Distilled Water	The most severe deterioration occurred in wet/dry experiments with 3M solutions and 194°F drying. Only four cycles (26 days) were required for observable visible damage.
	W/D	Wet at 140°F; dry at 140°F; 16 cycles		• Rectangular blocks **0.5 in. x 0.5 in. x 1 in.** cut from **High** durability PCC cores from in-service highways • Rectangular blocks **0.5 in. x 0.5 in. x 1 in.** cut from **Low** durability PCC cores from in-service highways	• 4.40% NaCl = 0.75 M • 8.33% $CaCl_2$ = 0.75 M • 7.15% $MgCl_2$ = 0.75 M • Distilled Water	The least damaging conditions were wet/dry cycling with 0.75M solutions and 140°F drying, and freeze/thaw cycling with 0.75M solutions and 32°F freezing. Each required 16 cycles (104 days) to produce significant deterioration.
	F/T	Freeze at -94°F; thaw at 77°F; 9 cycles		• Rectangular blocks **0.5 in. x 0.5 in. x 1 in.** cut from **High** durability PCC cores from in-service highways • Rectangular blocks **0.5 in. x 0.5 in. x 1 in.** cut from **Low** durability PCC cores from in-service highways	• 17.6% NaCl = 3 M • 33.3% $CaCl_2$ = 3 M • 28.6% $MgCl_2$ = 3 M • Distilled Water	
	F/T	Freeze at 32°F; thaw at 77°F; 16 cycles		• Rectangular blocks **0.5 in. x 0.5 in. x 1 in.** cut from **High** durability PCC cores from in-service highways • Rectangular blocks **0.5 in. x 0.5 in. x 1 in.** cut from **Low** durability PCC cores from in-service highways	• 4.40% NaCl = 0.75 M • 8.33% $CaCl_2$ = 0.75 M • 7.15% $MgCl_2$ = 0.75 M • Distilled Water	The least damaging conditions were wet/dry cycling with 0.75M solutions and 140°F drying, and freeze/thaw cycling with 0.75M solutions and 32°F freezing. Each required 16 cycles (104 days) to produce significant deterioration.

Lee et al 2000 [97] Iowa DOT	W/D	Immerse at 136.4°F for 132 hrs; dry at 136.4°F for 24 hrs; cool to 77°F; immerse at 77°F; store at 136.4°F for 132 hrs.	Not Cited	**Blocks cut from PCC cores** removed from Iowa highways (air content not given) **1.2 in. x 0.6 in. x 0.6 in.**	• 4.40% NaCl =0.75 M • 8.33% $CaCl_2$ = 0.75 M • 7.15% $MgCl_2$ = 0.75 M • CMA (5 ratios)=0.75M • Calcium Acetate=0.75M • Magnesium Acetate = 0.75M	This study observed that magnesium in any form was very damaging to the concrete. **Magnesium chloride** produced significant concrete crumbling because of widespread replacement of calcium silicate hydrate (C-S-H) with non-cementitious magnesium silicate hydrate (M-S-H). **Calcium magnesium acetate** solutions were the most damaging of all solutions tested.
	F/T	Immerse at 135°F for 132 hrs.; air cool to 77°F; place in freezer at 25°F for 24 hr; air warm to 77°F; immerse at 77 F, store at 135°F for 132 hrs.	Not Cited	**Blocks cut from PCC cores** removed from Iowa highways (air content not given) **1.2 in. x 0.6 in. x 0.6 in.**	• 4.40% NaCl =0.75 M • 8.33% $CaCl_2$ = 0.75 M • 7.15% $MgCl_2$ = 0.75 M • CMA (5 ratios)=0.75M • Calcium Acetate=0.75M • Magnesium Acetate = 0.75M ***N**OTES: The solutions used were 0.75 M CaCl2·2H2O, MgCl2 ·6H2O, NaCl, calcium acetate Ca(CH3COO)2·H2O, magnesium acetate Mg(CH3COO)2·4H2O, and CMA based on a molar ratio of 3:7, i.e. 3[Ca(CH3COO)2·H2O] :7[Mg(CH3COO)2·4H2O], and distilled water. Experiments were also conducted with five solutions of 0.75 M CMA with different molar ratios of Ca-acetate and Mg-acetate (5:3, 7:3, 1:1, 3:5, and 3:7).*	Wet/dry and freeze/thaw cycling in CMA produced widespread and severe damage with scaling from replacement of C-S-H with non-cementitious M-S-H. **Magnesium acetate** produced similar damage and **calcium acetate** solutions produced much less alteration. **Calcium chloride** deicing salts caused characteristic deterioration in concrete containing reactive dolomite coarse aggregate by enhancing dedolomitization reactions that release magnesium to form destructive brucite and M-S-H. For the experimental conditions utilized herein, **NaCl solution** was the least deleterious to the cement paste and aggregate. The validity of extrapolating the results obtained in our experimental conditions to those occurring under road use conditions is uncertain, and that our results and conclusions should be taken as cautionary only.

Sutter et al 2006 [98] Michigan Technological University **SD DOT**	Soak	Immerse at -15°F for 20 hours; Air dry at 135° F for 20 hours	Not Cited	**Mortar cylinders** (Ottawa Sand, cement and water only) **2 in. diam. X 4 in. H** w/c 0.40 w/c 0.50 w/c 0.60 air content not given	• 15% $MgCl_2$=1.85 m Mg2+ & 3.7 m Cl- *This $MgCl_2$concentration was chosen to represent the immediate dilution that occurs when salt solutions are applied to a road surface*. • 17% $CaCl_2$= 1.85 m Ca2+ & 3.7 m Cl- • 17.8% NaCl = 3.7 m Na & 3.7 m Cl-	***Not Successful, test stopped*** *Molality offers the advantage of equal numbers of moles of each deicer cation per volume solution, providing a basis for comparison of deicer chemicals in terms of the chemical interaction only.*
	Soak	Immerse at 40°F for 7, 14, 28, 56, 84 or 112 days	Not Cited	**Mortar cylinders** **2 in. diam. X 4 in. H** w/c 0.40 w/c 0.50 w/c 0.60 air content not given	• 15% $MgCl_2$ • 17% $CaCl_2$ • 17.8% NaCl	***Successful, but ended at 84 days*** Exposures of the various mortar specimens to calcium and magnesium chloride solutions at 40°F led to severe expansion, with deterioration first noticed at 56 days. Petrographic analysis and quantitative microanalysis were used to positively identify the presence of $Mg(OH)_2$ (brucite) formation in the outer layers of the specimens. Furthermore, the results presented clear evidence of calcium oxychloride formation in the specimens analyzed. Further research Phase 2 is being conducted, including the same immersion test at 40°F on Portland Cement Concrete specimens, to identify whether this distress mechanism is of concern for structures such as roads and bridges.
	Soak	Immerse at 135°F for 7, 14, 28, 56, 84 or 112 days	Not Cited	**Mortar cylinders** **2 in. diam. X 4 in. H** w/c 0.40 w/c 0.50 w/c 0.60 air content not given	• 15% $MgCl_2$ • 17% $CaCl_2$ • 17.8% NaCl	***This test Resulted in minimal deterioration of all specimens***

Wang, Nelson and Nixon, 2006 [99]Iowa State university	W/D	Immerse and store at 40°F for 15 hrs; air dry at 73°F (50% RH) for 9 hrs (solution changed every 20 cycles)	Not Cited	**Paste sample** **2 in. x 2 in. x 2 in.** Air entrainment 6% **Concrete sample** **4 in. x 4 in. x 4 in**. Air entrainment 6%	• 26.5% NaCl • 37.9% $CaCl_2$ • 39.9% $CaCl_2$ + inhibitor • 54.5% KAc • Agricultural = ?? • Distilled Water	Studied physical (mass loss and scaling), mechanical (strength), chemical (ion penetration and crystalline reaction products), and micro-structural properties of the paste and concrete were evaluated.
	F/T	Immerse and freeze at -4°F for 15 hrs; thaw for 9 hrs (not in solution) (solution changed every 10 cycles)	Not Cited	**Paste sample** **2 in. x 2 in. x 2 in.** Air entrainment 6% **Concrete sample** **4 in. x 4 in. x 4 in**. Air entrainment 6%	*DILUTED TO ALLOW FOR FREEZE to OCCUR in LAB* • 13.3% NaCl • 9.5% $CaCl_2$ • 10.0% $CaCl_2$ + inhibitor • 13.6% KAc • Agricultural (1:3) (chem:water) • Distilled Water	Results indicated that the various deicing chemicals penetrated at different rates into a given paste and concrete, resulting in different degrees of damage. Among the deicing chemicals tested, two **calcium chloride** solutions caused the most damage under both W/D and F/T conditions. Addition of a **corrosion inhibitor** into the calcium chloride solution delayed the onset of damage, but it did not reduce the ultimate damage. **Agricultural deicing product** resulted in the least chemical penetration and scaling damage of paste and concrete.
Darwin et al, 2008 [100] **University of Kansas**	W/D	Immerse at 73°F for 4 days; air dry at 100°F for 3 days (solutions replaced every 5 weeks) tested up to 95 cycles(weeks) *(Each 10 weeks is supposed to represent 10 years in field)*	Not Cited ***SEE NOTE***	**Prismatic PCC Specimens** **3 in. x 3 in. x 12 in.** w/c 0.45 air entrainment 6+/-1%	*Report states: Ice melting capability of a deicer is more closely related to the number of ions in a given quantity of water than to either the weight or molar concentration. Each test solution is molal ion concentration* • 15% NaCl = 6.04m • 16.9% $CaCl_2$ = 6.04m • 16.1% $MgCl_2$ = 6.04m • 22.7% CMA= 6.04m • Water • Air	• Visual Condition (physical appearance) • Change in Dynamic Modulus of Elasticity (ASTM C 215 based on ASTM C 666 for freeze/thaw)) At high concentrations, **calcium chloride, magnesium chloride, and calcium magnesium acetate** cause significant changes in concrete that result in loss of material and a reduction in stiffness and strength. The application of significant quantities of calcium chloride, magnesium chloride, and calcium magnesium acetate over the life of a structure or pavement will negatively impact the long-term durability of concrete.
		Immerse at 73°F for 4 days; air dry at 100 F for 3 days (solutions replaced every 5 weeks) tested up to 95 cycles(weeks)	Not Cited	**Prismatic PCC Specimens** **3 in. x 3 in. x 12 in.** w/c 0.45 air entrainment 6+/-1%	• 3% NaCl = 1.06m • 3.25% $CaCl_2$ = 1.06m • 3.76% $MgCl_2$ = 1.06m • 4.9% CMA = 1.06m • Water • Air	At lower concentrations, **sodium chloride and calcium chloride** have a relatively small negative impact on the properties of concrete. At high concentrations, **sodium chloride** has a greater but still relatively small negative effect. At low concentrations, **magnesium chloride and calcium magnesium acetate** can cause measurable damage to concrete.

NOTE*: Wet/dry cycles continue for a total of 95 weeks or until the relative dynamic modulus of elasticity (wet/dry) Pw/d drops below 0.9, at which point the tests are terminate*

Poursaee, Laurent, and Hansson, 2010 [101] **Purdue University**	W/D	A ponding well was filled with a salt solution corresponding to a 3% Cl– (weight percent) concentration for 2-week periods followed by 2 weeks without solution (cycled for 130 weeks)	Not Cited ***SEE NOTE***	**Mortar prisms (containing steel)** **6 in. × 6 in. × 4 in.** Contain four 9 in. lengths of #5 (6.35 mm or 0.25 in ø) steel reinforcing bars. Air content not reported	• 4.94% NaCl (3% Cl-) • 4.70% $CaCl_2$ • 4.03% $MgCl_2$	Determine the effect of each of these salts on the **corrosion of steel rebar and their impact on the durability of the mortar.** The results show that $CaCl_2$ has the most negative effect on the steel and, in high concentrations, on the integrity of the mortar. $MgCl_2$ also deteriorates the mortar if used in high concentration, while NaCl has no apparent effect on mortar durability even in high concentration.
University of Waterloo	W/D	A ponding well was filled with a salt solution corresponding to a **30%** Cl– (weight percent) concentration for 2-week periods followed by 2 weeks without solution		**Mortar prisms (containing steel)** **6 in. × 6 in. × 4 in.** Contain four 9 in. lengths of #5 (6.35 mm or 0.25 in ø) steel reinforcing bars	• 49.4% NaCl (30% Cl-) • 47.0% $CaCl_2$ • 40.3% $MgCl_2$	By increasing the salt concentration from 3% to 30%, severe deterioration was observed in the mortar specimens exposed to $CaCl_2$ and, to a lesser extent, in those exposed to $MgCl_2$. No damage was seen on the specimens exposed to NaCl.
NOTE: *The vertical surfaces were coated with epoxy resin to prevent access of oxygen from those surfaces; (ii) a ponding well was mounted on the top surface; and (iii) the three bottom bars were connected together and then connected to the top bar through a 100 Ω resistor.*						
Shi et al 2010[102] **Montana State University**	F/T	Freeze at -0.04°F for 16-18 hrs; thaw at 74.4°F (RH 45-55%) for 6-8 hr; repeat cycle 10 times	Modified SHRP H-205.8 freeze thaw test FESEM EDX	**PCC Cylinders** **1-1/2 in. dia x 1-7/8 in. H** Used four specimens per solution plus control = total of 32 test specimens Air entrainment 6+/- 1% 3% after compaction	*BELOW diluted 100 to ~3 with dionized water* • 99% Solid NaCl diluted to **3% solution** • 99% Solid Potassium Formate diluted to **3% solution** • 50% Liquid Potassium Acetate diluted to **1.5% solution** • 96% Solid CMA diluted to **3% solution** • 27-29% Liquid $MgCl_2$ diluted to **0.85% solution** • ?% Solid Ice-Slicer ™ (NaCl) diluted to **3% solution** • Solid Sodium Acetate, & Sodium Formate Blend (50:50) diluted to **3% solution**	"This work investigated the effect of diluted deicers on the durability of a Portland cement concrete. Based on the gravimetric and macroscopic observations of freeze/thaw specimens following the modified SHRP H205.8 laboratory test, de-ionized water, the CMA solid deicer, and the CDOT $MgCl_2$ liquid deicer were benign to the PCC durability, whereas KFm and the NaAc/NaFm blend deicer showed moderate amount of weight loss and noticeable deterioration of the concrete. NaCl, the NaCl-based deicer (IceSlicerTM), and the KAc-based deicer (CF7TM) were the most deleterious to the concrete. Our data indicated much more deleterious impacts by 3% NaCl than 0.85% $MgCl_2$ on PCC durability. The key was the difference in the deicer solution concentration." This finding from diluted deicers differed from the study of concentrated deicers [3], where NaCl seemed to be more chemically benign to concrete than $MgCl_2$. It should be cautioned that in the field environment, the deicer impact on the durability of concrete may not follow a similar pattern, as it is further complicated by the concentration and longevity of the deicer and its additives, the chemical composition and microstructure of the concrete, and the temperature regimes experienced by the concrete."

Shi et al 2011 [103] **Montana State University**	Soak	Ponded at room temperature for 330-347 days	Modified (NACE) Standard TM0169-95 for corrosion of carbon Steel	**Cores** removed from 1980s style **PCC** design (WADOT) **2.3 in. x 2.2 in. H** Pavement samples Air content 5.7% Bridge samples Air content 5.1%	*BELOW diluted 100 to ~31 with dionized water* • 23% NaCl diluted to **7.7% solution** • 23% NaCl+inhibitor (Shield GLT ™) diluted to **7.8% solution** • 30% $CaCl_2$ + inhibitor (Geomelt CT ™) diluted to **8.2% solution** • 30% $MgCl_2$ + inhibitor (Freezgard C1 Plus ™) diluted to **8.8% solution**	"To determine relative effect of various corrosion-inhibited deicers on the concrete durability, relative to the ''straight salt" (non-inhibited sodium chloride)."ASTM C873/C873M – 04e1 Standard Test Method for compressive Strength of Concrete Cylinders. The comparison between non-inhibited and inhibited NaCl suggests little benefits of corrosion inhibitor in preserving the concrete integrity in the case of continuous exposure to deicers at room temperature. One possible reason is provided as follows. The inhibitors added in deicer products were designed to mitigate the corrosive attack of chloride to metals (instead of concrete). For the pavement mix, the continuous exposure to non-inhibited NaCl, inhibited NaCl and the inhibited $CaCl_2$ deicer led to limited levels of strength gain of the concrete, whereas that to the inhibited $MgCl_2$ led to significant strength loss. For the bridge mix, the continuous exposure to the four deicers led to significant strength loss of the concrete, with the inhibited $CaCl_2$ deicer being the least affected. These results suggest the deleterious role of Mg_2+ cations and the beneficial role of Ca_2+ cations when it comes to their effect on the concrete integrity.
Jain et al 2012 [104] Purdue University	W/D	Immerse at 39.2°F for 16 hrs; dry at 50% RH 73.4 F for 8 hrs. 168-350 days (cycles) (1 cycle = 24 hrs)	Not Cited	1. **Plain Portland Cement Concrete** Air content 6.8% w/c = 0.42 2. **Fly Ash (20%) PCC** Air content 5.8% w/c = 0.42 • Prisms **3x3x11.5 in**. • Cylinders **4x8 in.** • Cylinders **3x6 in.**	• 23% NaCl = 10.20 molal ions • 28% $CaCl_2$ = 10.51 " " • 25% $MgCl_2$ = 10.5 " " • Deionized Water	Ultrasonic pulse velocity measurements after every two weeks of exposure until the end of the test (ASTM E1876). At the end of the W-D exposure period, the same test cylinders were used to obtain the (AASHTO T22-07) compressive strength of the concrete. In summary, based on the visual observations of Type I specimens exposed to W-D and F-T cycles, it can be concluded that the greatest physical changes resulted from exposure to $CaCl_2$ deicers, whereas the exposure to NaCl deicer and to the deionized water did not create any visible signs of distress. The visual damage induced by the exposure to the $MgCl_2$ was less extensive than that induced by exposure to $CaCl_2$ under both W-D and F-T conditions. The 20% Fly Ash concretes displayed better performance (less reduction in relative dynamic modulus of elasticity) than Type I concretes during the reported period of testing in both exposure regimes. This can be attributed to pozzolanic reaction and higher chloride-binding capacity of fly ash concretes.
	F/T	9 hrs cooling from 71.6°F to -4°F; 5 hrs at -4°F; 6 hrs heating from -4°F to 71.6°F; 4 hrs at 71.6°F; 168-350 days (cycles)		1. **Plain Portland Cement Concrete** 2. **Fly Ash (20%) PCC** • Prisms **3x3x11.5 in. (only)**	• 14% NaCl = 5.48 molal ions • 17% $CaCl_2$ = 5.54 " " • 15% $MgCl_2$ = 5.56 " " • Deionized Water	

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Connecticut Academy of Science and Engineering
805 Brook Street, Building 4-CERC, Rocky Hill, CT 06067-3405
Phone: 860-571-7143 • e-mail: acad@ctcase.org
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Connecticut Academy of Science and Engineering
805 Brook Street, Building 4-CERC, Rocky Hill, CT 06067-3405
Phone: 860-571-7143 • e-mail: acad@ctcase.org
web: www.ctcase.org