Environmental Life-Cycle Assessment of Winter Maintenance Treatments for Roadways

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Abstract: Departments of Transportation (DOTs) rely heavily on chloride-based treatments for winter road maintenance despite the well-documented effects of these chemicals on infrastructure and the environment. Proposed alternative treatments have yet to be widely adopted because of economic and technical limitations that are largely outside of the control of the DOT. This work explores the application of winter maintenance chemicals with a life-cycle approach to understand which actions a DOT can take to reduce the negative life-cycle environmental impacts of these activities. Three representative treatments and/or best management practices are compared: conventional rock salt, calcium magnesium acetate (CMA), and preemptive treatments of roadways with a brine of salt and/or CMA. The results 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 a brine rather than in the dry form results in important reductions in all environmental impacts over the entire life cycle. This result is consistent for a variety of climate conditions (e.g., representative of coastal, piedmont, and mountain climates) considered for this study, which used historical weather data from Virginia. Because DOTs can affect appreciable improvements in efficiency by using brines, sensitivity analysis identifies the activities specifically resulting in the most important environmental improvement on a systems basis. The DOT-controlled steps with the greatest potential for improvement include reducing the energy consumed for the salt application process and implementing practices that reduce total storm water runoff to reduce chloride loading. **DOI:** 10.1061/(ASCE)TE.1943-5436.0000453.

CE Database subject headings: Highways and roads; Maintenance; Winter; Life cycles; Ice; Environmental issues.

Author keywords: Roadway winter maintenance; Life cycle assessment; Environmentally preferable deicing.

Introduction

DOTs in the United States are responsible for treating roadways during winter weather events to ensure that the roads are safe for motorists. Most of these agencies rely on chloride-based deicing and antiicing compounds to perform this function because these compounds are inexpensive, effective, and many DOTs already have the capital equipment and expertise needed to handle and apply the chemicals (Transportation Research Board 1991). The most common chloride-based compound is sodium chloride (i.e., rock salt or NaCl), although magnesium chloride ($MgCl_2$) and calcium chloride ($CaCl_2$) are also frequently used. The production, distribution, and application of these compounds are generally considered interchangeable. A number of alternatives to chloride-based road treatments have been developed over the years, but these represent a small fraction of the market because they are significantly more expensive (Levelton Consultants 2007).

In spite of their heavy use, chloride-based road treatments have well-characterized detrimental effects on roadway infrastructure and on vehicles (Callahan 1989; Cody et al. 1996; Raupach 1996). As a result of these studies, a number of mitigation techniques have been developed to preempt the negative consequences of chloride use on roads. The reinforcing steel now used in most concrete roads is coated to extend its life, and automobiles are sold with fewer ferrous components exposed to the roadway (Koch et al. 2002). These stopgap measures have eliminated some of the effects that chlorides have on engineered systems, but chloride application remains the single biggest determining factor in the life of bridge decks and other infrastructure, from concrete pavements to sign and light posts (Transportation Research Board 1991).

In addition to affecting infrastructure, chloride-based compounds have well-documented burdens on the natural environment (Cain et al. 2001; Corsi et al. 2010; Hanes et al. 1970; Jones and Jeffrey 1986; Novotny et al. 1999). The published research is predominantly focused on three effects associated with chloride applications: (1) the effect of chloride contamination on ground and surface water; (2) soil contamination; and (3) vegetation stress. Direct runoff from the roadway has been shown to contain exceedingly high chloride levels after application, with a great deal of variability depending on precipitation conditions and road properties (Corsi et al. 2010). Watershed scale studies have demonstrated appreciable average accumulation of chloride over time, with chloride concentrations in some northern metropolitan areas exceeding U.S. Environmental Protection Agency chronic water quality levels even during the nonwinter maintenance period of May through

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Note. This manuscript was submitted on May 30, 2011; approved on August 7, 2012; published online on August 22, 2012. Discussion period open until July 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Transportation Engineering***, Vol. 139, No. 2, February 1, 2013. © ASCE, ISSN 0733-947X/2013/2-138-146/$25.00.

J. Transp. Eng. 2013.139:138-146.

October (Corsi et al. 2010). Similarly, the degree of soil contamination has been found to be dependent on the amount of highway drainage it receives (including splashing and spraying), slope, and soil type (Colwill et al. 1992). Both water and soil containing salt contribute to vegetation stress, as does direct salt accumulation on the foliage (Bowers and Hesterberg 1976).

Recognizing the engineering and environmental costs of chloride-based treatments, the Federal Highway Administration (FHWA) funded research aimed at identifying alternatives to these chemicals in the mid-1970s. Calcium magnesium acetate (CMA) is the most promising of the compounds to have emerged from those efforts. CMA has an ice melting capacity similar to that of NaCl, preliminary tests suggested that CMA had little to no effect on concrete and metal, and it was not harmful to plants or animals (Transportation Research Board 1991). CMA is a mixture of calcium and magnesium acetate and is produced by reacting acetic acid and dolomitic limestone (Wise et al. 1991). Since its discovery in the 1970s by Dunn and Schenk (1980), it has been evaluated extensively to understand its feasibility as an alternative to chloride-based treatments (California Department of Transportation 1989; Connolly et al. 1990; Horner 1988; Manning and Crowder 1989). There are some well-documented shortcomings of CMA: it has a high biochemical oxygen demand when undergoing decomposition in receiving waters, and it is expensive to manufacture relative to salts (Leineweber 1992). It is effective over a range of temperatures and is noncorrosive; so overall, it is considered to be one of the best alternative chemical deicers available. Its high purchase price, which tends to be an order of magnitude higher than rock salt per unit mass, has inhibited its widespread adoption (Basu et al. 1999; Leineweber 1992; Ormsby 1999; Yang et al. 1999).

In light of the significant infrastructure and environmental impacts of chloride treatments, a number of research studies have sought to quantify the full cost of applying these compounds. These studies have monetized the indirect costs associated with infrastructure degradation and automobile damage as well as the negative impacts to the natural environment (Environment Canada 2006; Yunovich et al. 2006). Vitaliano et al. (1992) estimated that the true cost of using salt for winter maintenance was approximately $800 per ton, as compared to its purchase price of approximately $50 per ton. Although the costs of salt and maintenance have increased since this 16:1 ratio was first calculated, the discrepancy between purchase price and true cost has persisted. Such estimates make CMA appear more competitive than chloride-based treatments. In practice, DOTs are not responsible for many of the externalities associated with chloride use, so it is unlikely that they will change their treatment given that their imperative is to clean the most lane miles as effectively and inexpensively as possible. The efforts to monetize the effects of using these treatments have a great degree of uncertainty inherent in their estimates because precise cost numbers are highly dependent on key variables, including the amount of chemical used over a specific period of time, the total volume of chemicals used, the type of system being maintained, and environmental conditions. Nevertheless, this full cost accounting does contribute to the perception that CMA might be an attractive alternative to chloride-based treatments (Levelton Consultants 2007).

Important considerations for DOTs when evaluating alternative road treatments are the investments in infrastructure and expertise needed for the distribution, storage, and application of rock salt. Within these constraints, DOTs have identified certain parameters that they can control to minimize the total amount of chemicals they use while maintaining service. For example, many DOTs have worked to cover their rock salt storage facilities because runoff from these facilities can result in significant, and easily avoided, flows of salt into the environment. Similarly, some DOTs have attempted to improve other handling practices, such as applying the treatments closer to the surface of the road to minimize material bouncing off the roadway surface, and others use road weather information systems to help optimize chemical application rates based on specific roadway conditions. Although these approaches have been useful in decreasing the amount of chlorides that enter the environment, few studies have attempted to assess the overall systems-level effects of winter road treatments from a life-cycle standpoint, and none have studied winter maintenance systems exclusively (Stripple 2001).

Life-cycle assessment (LCA) is a framework for evaluating the environmental impacts of products or processes over the entire life cycle, from resource extraction to end of life treatment. In the context of winter road treatment, an LCA would enable the comparison of all steps in the delivery and use of a product, from mining raw materials, manufacturing or processing the chemical, storage, and application, to eventual fate in the environment. Such a comparison would aid DOTs that have historically only had access to a few of the stages in the road-treatment life cycle. Much like full-cost accounting quantifies all the infrastructure and environmental costs of chloride-based treatments and its alternatives, LCA provides quantitative measurements of the environmental consequences of different decisions. In particular, the use of process-level life-cycle assessment, wherein the system is modeled by using each individual unit operation and process, enables a detailed sensitivity analysis. This information would be very useful for DOTs, chemical suppliers, and environmental scientists seeking improvements in winter road treatment processes. This paper reports on the development of a life-cycle model for three different winter maintenance approaches that could be used to maintain an acceptable level of service for a roadway during an average winter precipitation event. Both deicing and antiicing treatments are considered. Deicing implies that chemicals are not applied until after frozen precipitation has accumulated on the roadway surface, and antiicing involves the practice of applying chemicals to the roadway surface prior to the accumulation of frozen precipitation. Both processes involve different levels of application and different profiles of runoff. The model was developed for the state of Virginia because the geographic diversity of the state provided a useful contrast about how the model behaved for coastal, piedmont, and mountainous landscapes.

Life-Cycle Methodology

Three winter maintenance treatments were included in this study. The benchmark for the study was rock salt, modeled as dry, granular sodium chloride applied to the roadway following a small accumulation of frozen precipitation to the roadway surface. Subsequent applications of dry NaCl were used throughout the remainder of the storm event based on precipitation intensity and temperatures. This treatment is representative of the approach used by most DOTs. The second approach was to apply a concentrated sodium chloride solution or brine followed by the application of granular NaCl that had been prewetted with brine. This antiicing strategy requires that DOTs apply the brine solution before the onset of the storm event to prevent the formation of a bond between the frozen precipitation and the road surface. Prewetting the granular NaCl for subsequent applications allows the sodium chloride to mix with water on the roadway more readily once applied, and it results in less bouncing off of the granular sodium chloride from the road during application. Brine application does require different

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equipment to store, load, and apply the liquid treatment, so it is not a widespread practice, although it provides efficiency benefits over the conventional dry application of sodium chloride. The third and final treatment was a calcium magnesium acetate solution. CMA is used for antiicing in the brine form before the weather event but can also be applied in the prewetted granular form after the onset of the storm. The CMA approach is similar to the brine NaCl method because it requires that DOTs obtain specialized storage and application equipment and more expensive chemicals.

The life-cycle model was developed to analyze the environmental impacts resulting from the acquisition of chemicals, transportation to storage, loading, and application to the roadway. The upstream system boundaries were drawn around the mining of NaCl for the two salt-based alternatives, and around the mining of dolomite and acetic acid production for the CMA-based approach. The allocation of burden on these upstream processes was performed by using a mass-basis because mining operations have large burdens but produce commodities for a number of industries, not just the winter maintenance chemical industry. The downstream extent for all three approaches included the disposal of runoff from the DOT storage facilities and the fate of runoff from the roadway. The environmental burdens for each of the steps identified was estimated with a combination of sources, including those available in the literature, previous research conducted by the authors, and from SimaPro Life Cycle Analysis life-cycle assessment software using the ecoinvent database.

The model was built in spreadsheet format using the Oracle Crystal Ball modeling plug-in, which enabled a stochastic comparison of the data. The model allowed each input to be entered as a range or distribution depending on the availability of data. Each output was generated in the form of a distribution, which allowed the authors to provide meaningful estimates of the uncertainty associated with model predictions. The functional unit for the assessment was selected to be 100 lane miles. The model was built such that a number of key assumptions could be varied to explore their effect on the final results. For example, the chemical application rates, which are generally subject to guidelines but are variable in practice, could be changed to understand their effect on the results. Similarly, the total number of applications could be varied. Equivalent chemical volumes for each of the three approaches were based on information developed in the National Cooperative Highway Research Program's *Project 6-13* (Blackburn et al. 2004). This study provided the equivalent application rates for several ice control chemicals, accounting for pavement temperature, initial ice-pavement bonding conditions, and dilution potential based on forecasted precipitation rates. Having the flexibility within the model to adjust these rates was important because the relationship between the volume of NaCl to CMA used was not constant. For example, as pavement temperature decreases, the relative amount of CMA needed to adequately treat a given distance of roadway increases more readily than it does for sodium chloride.

The three winter maintenance treatments were evaluated on the basis of five relevant environmental impact factors. The first was total chloride emissions to the environment. Contamination of both surface and ground waters by runoff from salt application has been the primary concern related to the use of chloride-based treatments. The second was biochemical oxygen demand (BOD). Alternatives to chloride-based treatments (such as CMA) are known to contribute to the BOD loading of receiving waters. The degradation of the organic constituents in these chemicals can result in a temporary reduction in the dissolved oxygen levels in receiving waters. The third impact factor was total energy use. Energy consumption resulting from the production and application of each chemical treatment was estimated and reported. These results are of interest because energy use is often strongly correlated with the price of a treatment, and because most energy is derived from fossil-based fuels, it is proportional to the use of nonrenewable resources upstream. The fourth impact factor considered was total greenhouse gas (GHG) emissions. DOTs are becoming increasingly pressured to reduce their GHG emissions, but few efforts have been undertaken to evaluate the effect that winter maintenance could have on climate change. The fifth and final impact factor included in this study was overall fresh water consumption. Water was included because two of the methods studied would require the production of an aqueous solution prior to application and could be an environmental consequence of interest in more arid locations.

The model was run for the average temperature and precipitation conditions typically found in the three geographic regions of Virginia; mountain, piedmont, and coastal; during the months of November–March. To determine these regional averages, 10–15 years of hourly temperature and precipitation data collected at three weather stations within each region were downloaded from the National Oceanic and Atmospheric Administration's National Climatic Data Center (National Oceanic and Atmospheric Administration 2011). These data were analyzed to capture only those events during which precipitation occurred and the temperature was below freezing. This enabled the authors to estimate the storm durations for each region. Along with the storm conditions (e.g., temperature), it was possible to calculate the number of applications of each particular treatment type being analyzed.

Following the initial model runs, a sensitivity analysis was conducted in which the magnitude of each input was varied by 10% while holding all other inputs constant. The resulting change in each of the model outputs was recorded and compared. Next, the processes contributing to each of the environmental burdens were separated into two groups: (1) those not in the direct control of the transportation agency (i.e., those upstream); and (2) transportation agency-controlled steps. The sensitivity analyses were rerun for all three approaches, and only those processes or steps within the control of the transportation agency were adjusted. Based on the model output, comparisons were made across each of the five impact categories. Similarly, the total environmental burdens for each of the three winter maintenance approaches were calculated.

System Boundaries

A schematic of the primary process steps for each of the three treatment strategies studied is presented in Fig. 1, and the data sources for each of the steps making up these processes are shown in Table 1. Although there is some overlap between the three in terms of storage and application, key differences were found to result in important environmental impacts. The boundaries set for each system are described in this section.

Salt

Fig. 1(a) shows the unit operations used in the application of rock salt. This treatment involved the fewest number of steps. In addition to the mining of NaCl, there were several transportation steps, storage, and loading steps. The disposal of NaCl runoff generated at DOT storage facilities also required the transport of large quantities of captured runoff to an offsite disposal facility.

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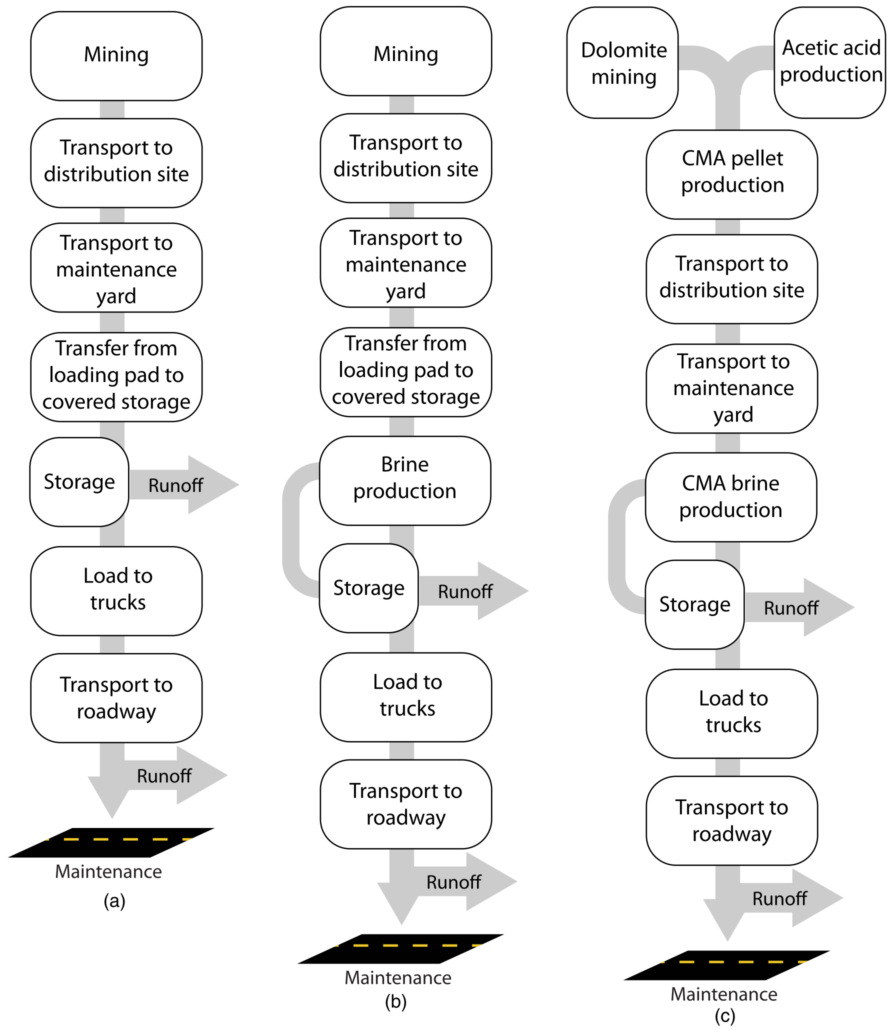

Fig. 1. Three road treatment processes: (a) rock salt; (b) sodium chloride brine; (c) calcium magnesium acetate (CMA)

Brine

The process steps involved in the storage and delivery of brine-based winter treatment are presented in Fig. 1(b). The delivery of brine involved many of the same processes involved in the delivery of salt, with additional steps needed to obtain water, create the approximately 23% aqueous brine solution (simply referred to here as brine), and the application of the brine with trucks specifically designed to haul and apply liquid cargo. This approach also required additional loading and storage steps but generally produced far less runoff than solid sodium chloride storage and application.

CMA

The steps required for the delivery of calcium magnesium acetate are presented in Fig. 1(c). The CMA was manufactured by using dolomitic limestone, which was mined, and acetic acid. Although there are several industrially viable methods for producing CMA, one method used natural gas for the production of a concentrated acetic acid solution that was then sprayed on dry lime to form CMA pellets. Because it is the most prevalent method, it was selected for modeling in this study (Transportation Research Board 1991). Upon delivery at the storage location for the DOT, CMA's storage and application steps in its life cycle resemble those of sodium chloride brine. The similarities in handling and application between CMA and rock salt partially explain why many DOTs perceive CMA as an attractive alternative to sodium chloride.

Results and Discussion

Winter maintenance using dry NaCl, brine, and CMA were compared on the basis of five environmental impacts over the entire life cycle, and results are summarized in Table 2. The sodium-chloride-based treatments were found to have significantly lower environmental impacts than CMA over the entire life cycle for four of five impact areas. The standard deviation for each value is also presented. The model output distributions were all lognormal. Also presented in Table 2 are the differences in emissions among the different treatment techniques to highlight the savings or increases in emissions or cost that would result from alternate treatments. The cost estimates came from Koch et al. (2002).

The total life-cycle energy required to deliver CMA was almost 10 times higher than rock salt and 15 times higher than brine. Most of this energy was consumed during the manufacture of CMA. The acetic acid needed to manufacture CMA was produced by first converting natural gas (methane) to methanol and then converting methanol to acetic acid by way of methanol carbonylation. This natural gas requirement manifested itself in the high price for CMA. Additional research has been sponsored by the FHWA in the hopes of identifying a less expensive method of producing

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Table 1. Data Sources for the Primary Steps for All Three Winter Maintenance Treatment Methods

Process step	Data source
NaCl mining	ecoinvent
Acetic acid production	ecoinvent
Dolomite mining	ecoinvent
Transport distribution	ecoinvent
Transport to maintenance yard	ecoinvent
Transfer to covered storage	Frey et al. (2010); USEPA (2005); Zapata and Gambatese (2005)
Brine production	Craver et al. (2008); U.S. Dept. of Energy and USEPA (2000)
Storage	Novotny et al. (1999); Fitch et al. (2005); Snodgrass and Morin (2000)
Load on brine application trucks	USEPA (2005); U.S. Dept. of Energy and USEPA (2000)
Load on salt application trucks	Frey et al. (2010); Zapata and Gambatese (2005)
Transport: Brine roadway application	ecoinvent; Alleman et al. (2004); Ketcham et al. (1996); Wisconsin DOT (2005)
Transport: Salt roadway application	ecoinvent
Storm water runoff	Novotny et al. (1999); Blackburn et al. (2004); Snodgrass and Morin (2000); Tanner and Wood (2000); Horner (1988)
Roadway maintenance	Shi et al. (2010); Shi et al. (2009); Bacchus (1987)

the acetic acid needed for the production of CMA. Although several methods of production have been explored and some appear promising, to date, none have proven to be feasible for mass production (Leineweber 1992). Like CMA, most of the energy required to apply both salt and brine was associated with upstream resource extraction. Interestingly, brine consumed more than one third less energy than dry rock salt. Although brine application required several additional steps that consumed energy (e.g., pumping for brine production and loading of brine tanks), it used less salt on a net basis, so the large upstream energy demands associated with mining could result in these important reductions in life-cycle energy demand. Consistent with the energy results, CMA generated the largest GHG emissions. The emissions were four to five times greater than the other two methods. Again, because the synthesis of the acetic acid required for CMA was assumed to be dependent on the use of natural gas, equivalent CO_2 emissions were high. However, per unit of energy, GHG emissions were lower for natural gas than for petroleum-based energy sources, and this resulted in CMA having lower GHG emissions relative to its total energy requirements.

In terms of water consumption, the disparity between CMA and the chloride-based treatments is even more pronounced. The CMA production process consumed appreciable amounts of water both in the production of the acetic acid and in the actual processing of the chemical into its pelletized form. The volume of water used to produce the brine and the CMA solution that were applied to roads represented less than 1% of the total amount used in both these systems. More than 90% of the water needed for these methods was used in resource extraction. This contradicted the assertion that use of brine for road treatment would disproportionately increase water consumption in the treatment process. Even more pronounced differences between the treatments were observed when considering the biochemical oxygen demand of the treatments. The total BOD emissions associated with CMA production were approximately 600 and 1,000 times greater than for NaCl and brine, respectively. This burden came largely from acetic acid production but also from the runoff following application. CMA is an organic chemical that contributes to the BOD of receiving waters in a way that the chloride compounds do not. Because as much as 75% of the total CMA volume applied ultimately ended up in water bodies (Horner 1988), this method represents a significant drawback to adopting CMA. For any given location, these estimates might be much higher or lower depending on the dilution potential of the receiving streams, but given the dramatic difference between the treatment chemicals, the effect of CMA is likely to always be greater than rock salt, regardless of hydrologic conditions (Horner 1988).

As expected, the one impact factor for which CMA was a major improvement was chloride emissions to the environment. Both the salt and brine systems emitted more than 30 times more chloride than CMA. Most of these emissions occurred as a direct result of runoff from treated lanes. In total, it was estimated that approximately 20,400 kg of Cl^- were released per 100 lane miles during a typical storm in the piedmont region of Virginia. This compared to only 530 kg Cl^- released when using CMA. Treating the roads with brine released 13,000 kg Cl^-, or approximately 36% less than the salt approach.

The results presented in Table 2 indicate that CMA, often touted as the environmentally preferable alternative to chloride-based winter maintenance chemicals, has life-cycle environmental burdens that are higher than conventional treatments. In four of five impact areas included in this study, CMA performed many times worse than the chloride-based options. Although the comparison of impact factors involves value judgments that an LCA cannot address (e.g., in some cases it might be desirable to reduce chloride emissions to a watershed at the cost of increased energy use and emissions upstream), the overall picture suggests that CMA does not reduce overall environmental burdens as intended. Expanding the system boundaries to include externalities to the transportation agency (e.g., infrastructure maintenance costs and/or salt impact abatement techniques like corrosion inhibitors for metals, epoxy coated rebar, or the annual washing of structures) or to the user (e.g., corrosion to vehicles that could result in safety or environmental concerns) would almost certainly affect the calculations, but it is unlikely that it would affect the conclusions. The burden estimates reported in this study are typically one order of magnitude higher for CMA than for conventional treatments, except for chloride emissions. As discussed, most estimates for the

Table 2. Environmental Burdens Associated with Three Winter Maintenance Approaches

Maintenance approach	Energy use (MJ) $\times 10^4$	GHG emissions (kg) $\times 10^3$	Water use (m^3) $\times 10$	Cl emissions (kg) $\times 10^3$	BOD (kg) $\times 10^2$	Cost ($/storm)
Salt (dry NaCl)	13.2 ± 6.0	10.5 ± 2.9	23.3 ± 5.7	20.4 ± 2.0	0.20 ± 0.07	3,149
Brine (NaCl brine)	8.7 ± 3.7	6.7 ± 1.9	15.0 ± 3.5	13.0 ± 1.4	0.12 ± 0.04	3,343
CMA (CMA brine)	129.3 ± 23.0	40.7 ± 6.9	580.2 ± 6.3	0.53 ± 0.2	135.8 ± 55.2	26,363
Δ_{Brine} (Brine–salt)	−4.5	−3.8	−8.3	−7.4	−0.08	194
Δ_{CMA} (CMA–salt)	116.1	30.2	556.9	−19.9	135.6	23,214

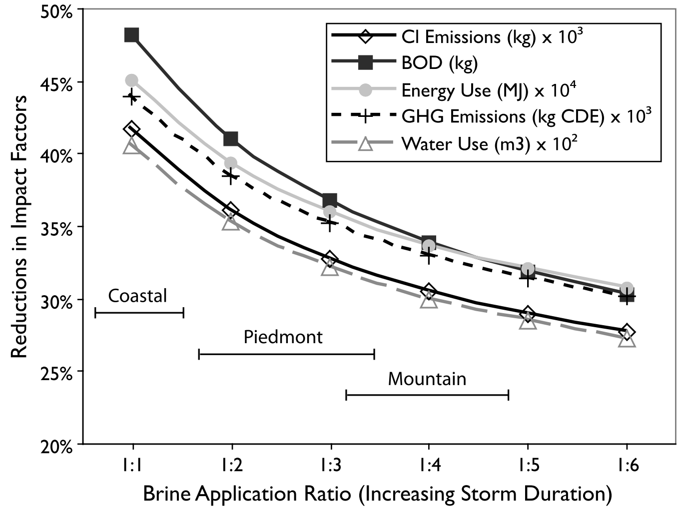

Fig. 2. Effect of brine application to solid chemical application ratios driving the environmental impacts of winter maintenance

true cost of salt are that it is roughly one order of magnitude higher than its purchase price (Vitaliano 1992). Although there are some effects that Vitaliano did not incorporate, such as the premature replacement of vehicles or the emissions from rusted exhaust systems, expanding the system boundaries could result in ambiguous results that, at best, would raise questions about the long-term environmental sustainability of either maintenance technique. More immediately, the data in Table 2 suggest that brine solutions of salt could result in important reductions in all impact areas modeled when compared to dry rock salt. Improvements of 30–40% for all impact factors are possible by using brine rather than dry sodium chloride. DOTs have the ability to switch to brine with minimal start-up costs.

The Base Case results presented in Table 2 were calculated by using time-averaged temperature, storm duration, and storm intensity data characteristic of the piedmont region of Virginia. Because these average weather parameters are different for the other two geographic regions of Virginia, so too are the maintenance protocols used to treat the average storms for those areas. To determine how the environmental burdens differed between dry salt applications and the use of brine for the three regions, the model was run with varying storm duration or intensity values, resulting in different pretreatment to in-storm-treatment ratios (or brine application ratios). The effect of brine composition was explored for each of the impact factors studied, and the results are presented in Fig. 2. They suggest that, in general, as storm duration and/or intensity increased (as was the case when moving from coastal to piedmont to mountain regions), there was a decrease in the environmental benefits of using the brine winter maintenance approach in place of dry salt. This is because pretreatment with brine—and the advantage it provides by reducing the volume of salt needed for treatment—only occurs once, regardless of the length of the storm. Because the ratio of pretreatment to in-storm-treatments changed with storm duration, the environmental benefits derived from the use of brine became less with increasing storm length. The environmental advantages of using brine were maximized for those areas where small, frequent storms occurred (i.e., the coastal region of Virginia). Such areas normally experienced small storms that had durations of fewer than 12 h. Areas that normally had storm durations longer than approximately 18 h still would see relatively large decreases in total environmental burdens if using brine in place of dry salt. The results of this sensitivity analysis were to ensure that the functional unit of lane miles treated was applicable to as wide a range of locations as possible.

Implications for Departments of Transportation

The life-cycle results presented in this paper provide a new perspective on those attributes that constitute an environmentally preferable winter maintenance treatment. It is important to delineate between those impacts that can be controlled by the transportation agency and those that originate upstream. Of course, all impacts are ultimately the direct result of treatment selection by the decision maker at the transportation agency, but other decisions can affect the overall burdens of winter maintenance. It was useful to explore the breakdown of the effects as shown in Fig. 3. Those operations impacts performed by the DOT are shaded gray and those occurring upstream are black.

With the exception of BOD and salt runoff to receiving waters, most of the impacts associated with winter maintenance did not occur where the road was located but instead originated upstream where the treatment chemical was produced. This suggests that fewer opportunities exist for improvement via best management practices and other activities that are typically touted as effective means to reduce the effects from winter maintenance. Production improvements in efficiency could result in important reductions in

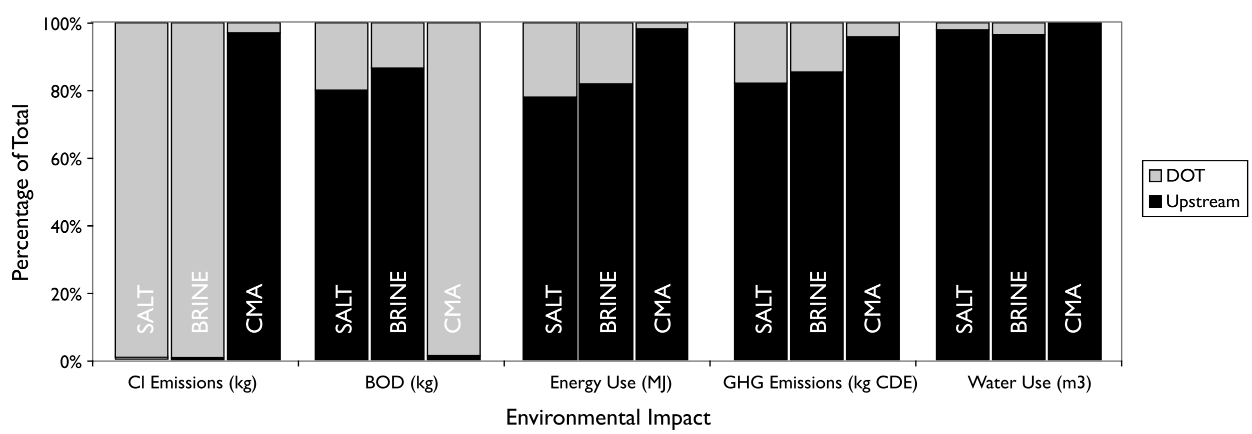

Fig. 3. Distribution of burdens (upstream versus at the DOT) for each impact factor clearly showing that although DOT decision makers can influence certain emissions (e.g., Cl emissions, BOD, and to a lesser extent, energy and GHGs emission), their influence is highly constrained in other regards (impacts expressed as a percent of total)

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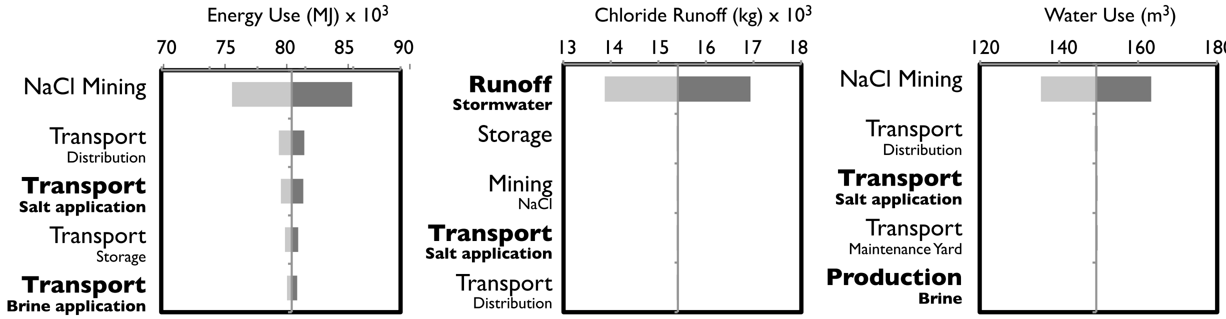

Fig. 4. Sensitivity analysis for energy use, chloride emissions, and water use for brine, indicating the steps that have the greatest effect for each impact area (bold steps are those controlled by the DOT; remaining steps occur during chemical production or transport to the DOT)

many of the impact areas reported but will ultimately have to be performed by the industries serving the DOTs. For the case of salt emissions to the environment, the transportation agency has almost all of the responsibility.

To provide additional insight into those processes that a transportation agency can control, a sensitivity analysis was performed on the model. Tornado plots were generated to depict the sensitivity of each impact factor to the model inputs. The results for total energy use, chloride emissions, and water use for the brine case are presented in Fig. 4. Those parameters that can be controlled by the DOT are in bold. The energy use plot suggests that improving the energy consumed for the transportation of salt, from the DOT maintenance yard to the roadway where it is applied, results in the greatest variance in the total energy consumption, from a DOT operations standpoint. While the system is considerably more sensitive to the way in which NaCl mining is performed, DOTs do not have direct control over these practices and as such, are unable to individually manage this aspect of the life cycle. DOTs do represent significant customers for salt producers and as such, could pressure the industry to streamline its operations. DOTs could realize the greatest reduction in energy consumption by improving the transportation processes used for chemical application. Examples of this might be improving the energy efficiency of the fleet used for application or optimizing the routing process used by application trucks. The chloride emissions plot clearly shows that reducing runoff containing salt has the greatest potential for minimizing the total amount of chlorides entering the environment. The water consumption plot indicates that most of the water needed for this treatment option is used during the mining process and; by comparison, the volume of water used for the production of brine is very small.

Conclusions

A life-cycle assessment of leading winter road maintenance techniques used in Virginia was performed to evaluate their overall burdens. The results suggest that CMA, which has been long considered one of the most environmentally promising treatment chemicals available to transportation agencies, has significantly higher emissions than chloride-based treatments. As expected, CMA does reduce overall chloride emissions relative to salt treatment, but this comes at the cost of significantly higher life-cycle energy, water, BOD, and greenhouse gas emissions. Most of the emissions associated with using CMA occur upstream of the DOT, during the mining and production of the base materials. Consequently, it is unlikely that DOTs can further reduce the effects associated with the use of this chemical by improving their application or management practices. Any significant improvements associated with the environmental burden of this alternative will almost certainly need to come from improvements in the production process.

Of the three approaches evaluated in this paper, the use of brine appears to be the best option available to DOTs. This option requires less total energy, releases fewer GHGs, consumes less water, and emits less BOD than either CMA or dry salt. The benefits of using brine over using dry salt were significant, typically on the order of 30–40%. The storm conditions were found to have an important effect on the savings that could be realized by using brine. Several different geographic regions of Virginia were modeled with different characteristic storm durations and intensities. For regions where storm intensities tended to be relatively mild, the benefits associated with using brine were even more significant.

A sensitivity analysis revealed several specific activities at the transportation agency with the greatest effect on emissions. In particular, the transportation of salt during the application process was found to be the highest energy-consuming DOT-controlled step; runoff from the roadway was the highest contributor to the total chloride emissions, and the volume of water needed for brine production was extremely small compared to the total water used for the salt mining process.

Although this result does not point to any obvious approaches that will eliminate the environmental impacts associated with the winter maintenance of roadways, this study does suggest that modest steps at the DOT level can result in meaningful reductions in life-cycle effects. In particular, a switch to using salt brine as a treatment method, rather than rock salt, enhances efficiency and reduces total energy use, water use, and greenhouse gas emissions without requiring a significant financial investment by the DOT. This "low hanging fruit" is a good example of how DOTs can simultaneously improve their environmental footprint and their economic bottom line while achieving a more sustainable winter treatment.

References

Alleman, J. E., Partridge, B. K., and Yeung, L. (2004). "Innovative environmental management of winter salt runoff problems at INDOT yards." *FHWA/IN/JTRP-2001/27*, Purdue Univ. Joint Transportation Research Project, West Lafayette, IN.

Bacchus, A. (1987). "Financial implication of salt vs. CMA as a deicing agent: Costs and benefits estimated by an MTO expert group." *Rep. ME-87-2*, Research and Development Branch, Ontario Ministry of Transportation, Toronto, Ontario, Canada.

Basu, R., et al. (1999). "Calcium magnesium acetate at lower production cost: Production of CMA deicer from biomass." Research and Development, Turner-Fairbank Highway Research Center, Federal Highway Administration, U.S. Dept. of Transportation, Washington, DC.

J. Transp. Eng. 2013.139:138-146.

Blackburn, R. R., Bauer, K. M., Amsler, D. E., Boselly, S. E., and McElroy, A. D. (2004). "Snow and ice control: Guidelines for materials and methods." *Final Rep. Project 6-13*, Midwest Research Institute, National Cooperative Highway Research Program (NCHRP), Kansas City, MO.

Bowers, M. C., and Hesterberg, J. H. (1976). "Environmental implication of highway deicing agents on white pine in Marquette County, Michigan." *Mich. Bot.*, 15(2), 75–89.

Cain, N. P., Hale, B., Berkalaar, E., and Morin, D. (2001). "Review of the effects of NaCl and other road salts on terrestrial vegetation in Canada." Commercial Chemicals Evaluation Branch, Environment Canada, Ottawa, Ontario, Canada.

California Dept. of Transportation. (1989). "A summary of CMA use and research and development, specifically in California." Technical Rep., Div. of Technology and Research, Sacramento, CA.

Callahan, M. R. (1989). "Deicing salt corrosion with and without inhibitors." *Transportation Research Record 1211*, Transportation Research Board, Washington, DC, 12–17.

Cody, R. D., Cody, A. M., Spry, P. G., and Gan, G. (1996). "Experimental deterioration of highway concrete by chloride deicing salts." *Environ. Eng. Geosci.*, 2(4), 575–588.

Colwill, D. M., Thompson, J. R., and Rutter, A. J. (1992). "An assessment of the condition of shrubs along motorways." *Rep. 1061*, U.K. Transport and Road Research Laboratory, Crowthorne, Berkeshire, England.

Connolly, J. P., Paquin, P. R., Mulligan, T. J., Wu, K., and Devanzo, L. (1990). "Calcium magnesium acetate biodegradation and its impact on surface water." Institute of Ecology, Univ. of California, Davis, CA.

Corsi, S. R., Graczyk, D. J., Geis, S. W., Booth, N. L., and Richards, K. D. (2010). "A fresh look at road salt: Aquatic toxicity and water-quality impacts on local, regional, and national scales." *Environ. Sci. Technol.*, 44(19), 7376–7382.

Craver, V. O., Fitch, G. M., and Smith, J. A. (2008). "Recycling of salt-contaminated stormwater runoff for brine production at Virginia Department of Transportation road-salt storage facilities." *Transportation Research Record 2055*, Transportation Research Board, Washington, DC, 99–105.

Dunn, S. A., and Schenk, R. U. (1980). "Alternative highway deicing chemicals." *Rep. No. FHWA-RD-79-108*, Federal Highway Administration, Washington, DC.

ecoinvent Version 2.0 [Computer software]. ecoinvent Centre, c/o Empa/ Technology and Society Lab (TSL), St. Gallen, Switzerland.

Environment Canada. (2006). "Winter road maintenance activities and the use of road salts in Canada: A compendium of costs and benefits indicators." *Road salts: Reducing the risk of road salts to the environment while keeping our roads safe*, The Green Lane, Environment Canada's world wide web site, ⟨http://www.ec.gc.ca/nopp/roadsalt/reports/en/winter.cfm⟩ (Mar. 31, 2011).

Fitch, G. M., Bartelt-Hunt, S., and Smith, J. A. (2005). "Characterization and environmental management of storm water runoff from road salt storage facilities." *Transportation Research Record 1911*, Transportation Research Board, Washington, DC, 125–132.

Frey, H. C., Rasdorf, W., and Lewis, P. (2010). "Comprehensive field study of fuel use and emissions of nonroad diesel construction equipment." *Transportation Research Record 2158*, Transportation Research Board, Washington, DC, 69–76.

Hanes, R. E., Zelazny, L. W., and Blazer, R. E. (1970). "Effects of deicing salts on water quality and biota—Literature review and recommended research." *Rep. 91*, National Cooperative Highway Research Program (NCHRP), Highway Research Board, Washington, DC.

Horner, R. R. (1988). "Environmental monitoring and evaluation of calcium magnesium acetate (CMA)." *Rep. 305*, National Cooperative Highway Research Program (NCHRP), Transportation Research Board, Washington, DC.

Jones, P. H., and Jeffrey, B. A. (1986). "Environmental impact of road salting—State of the art." *Technical Rep. RR237*, Ontario Ministry of Transportation, Ottawa, Ontario, Canada.

Ketcham, S. A., Minsk, L. D., Blackburn, R. R., and Fleege, E. J. (1996). "Manual of practice for an effective anti-icing program: A guide for highway winter maintenance personnel." *FHWA-RD-95-202*. Turner-Fairbank Highway Research Center, Office of Engineering Research and Development, Federal Highway Administration, McLean, VA.

Koch, G. H., Brongers, M., Thompson, N. G., Virmani, Y. P., and Payer, J. H. (2002). "Corrosion cost and preventive strategies in the United States." *Rep. No. FHWA-RD-01-156*, Office of Infrastructure Research and Development, Federal Highway Administration U.S. Dept. of Transportation, Washington, DC.

Leineweber, D. B. (1992). "Production of calcium magnesium acetate (CMA) from dilute aqueous solutions of acetic acid." Master of Science thesis, Univ. of Wisconsin, Madison, WI.

Levelton Consultants. (2007). "Guidelines for the selection of snow and ice control materials to mitigate environmental impacts." *Rep. 577*, National Cooperative Highway Research Program (NCHRP), Richmond, British Columbia, Canada, 208.

Manning, D. G., and Crowder, L. W. (1989). "Comparative field study of the operational characteristics of calcium magnesium acetate and rock salt." *Transportation Research Record 1246*, Transportation Research Board, Washington, DC, 18–26.

National Oceanic and Atmospheric Administration. "Unedited local climatological data." ⟨http://cdo.ncdc.noaa.gov/ulcd/ULCD⟩ (Mar. 16, 2011).

Novotny, V., Smith, D. W., Kuemmel, D. A., Mastriano, J., and Bartosova, A.(1999). "Urban and highway snowmelt: Minimizing the impact on receiving water." Water Environment Research Foundation, Alexandria, VA.

Oracle Crystal Ball version 11.1.2 [Computer software]. Oracle, Redwood Shores, CA.

Ormsby, W. C. (1999). "New technologies improve cost-effectiveness of CMA." *Public Roads*, 63(3), 2–9.

Raupach, M. (1996). "Chloride-induced macrocell corrosion of steel in concrete—Theoretical background and practical consequences." *Constr. Build. Mater.*, 10(5), 329–338.

Shi, X., Akin, M., Pan, T., Fay, L., Liu, Y., and Yang, Z. (2009). "Deicer impacts on pavement materials: Introduction and recent developments." *Open Civ. Eng. J.*, 3(1), 16–27.

Shi, X., Fay, L., Peterson, M. M., and Yang, Z. (2010). "Freeze-thaw damage and chemical change of a portland cement concrete in the presence of diluted deicers." *Mater. Struct.*, 43(7), 933–946.

SimaPro Life Cycle Analysis version 7.1 [Computer software]. PRé Consultants, Amersfoort, Netherlands.

Snodgrass, W. J., and Morin, D. (2000). "Patrol (maintenance/ works) yards. Supporting document for the road salts PSL assessment." Rep. submitted to Environment Canada CEPA Priority Substances List Environmental Resource Group on Road Salts, Commercial Chemicals Evaluation Branch, Environment Canada, Hull, Quebec, Canada.

Stripple, H. (2001). *Life-cycle assessment of road: A pilot study for inventory analysis*, 2nd Revised Ed., IVL Swedish Environmental Research Institute, Gothenburg, Sweden.

Tanner, D. Q., and Wood, T. M. (2000). "The effects of calcium magnesium acetate (CMA) deicing material on the water quality of Bear Creek, Clackamas County, Oregon, 1999." *Water-Resources Investigations Rep. 00-4092*, USGS, Portland, OR.

Transportation Research Board. (1991). "Highway deicing: Comparing salt and calcium magnesium acetate." *Special Rep. 235*, Washington, DC, 180.

U.S. Dept. of Energy, and U.S. Environmental Protection Agency (USEPA). (2000). "Carbon dioxide emissions from the generation of electric power in the United States." ⟨http://www.eia.doe.gov/cneaf/electricity/page/co2_report/co2emiss.pdf⟩ (Mar. 31, 2011).

U.S. Environmental Protection Agency (USEPA). (2005). "Emission facts: Average carbon dioxide emissions resulting from gasoline and diesel fuel." *EPA420-F-05-001*, Office of Transportation and Air Quality, Washington, DC.

Vitaliano, D. F. (1992). "An economic-assessment of the social costs of highway salting and the efficiency of substituting a new deicing material." *J. Policy Anal. Manage.*, 11(3), 397–418.

Wisconsin Dept. of Transportation. (2005). “Anti-icing technique.” *Guideline 32.35, state highway maintenance manual*, Bureau of Highway Operations, Madison, WI.

Wise, D. L., Levendis, Y. A., and Metghalchi, M. (1991). *Calcium magnesium acetate: An emerging bulk chemical for environmental applications*, Elsevier, New York.

Yang, S., Huang, Y. L., Jin, Z., Huang, Y., Zhu, H., and Qin, W. (1999). “Calcium magnesium acetate at lower-production cost: Production of CMA deicer from cheese whey. *Publication No. FHWA-RD-98-174*, Federal Highway Administration, Washington, DC.

Yunovich, M., Thompson, N. G., Balvanyos, T., and Lave, L. (2002). “Highway Bridges.” Appendix D, Corrosion Cost and Preventive Strategies in the United States. G. H. Koch, M. Po, H. Broongers, N. G. Thompson, Y. P. Virmani, and J. H. Payer, eds., Report No. *FHWA-RD-01-156*, Federal Highway Administration, McLean, VA, 773, ⟨http://www.dnvusa.com/Binaries/highway_tcm153-378806.pdf⟩ (Nov. 1, 2012).

Zapata, P., and Gambatese, J. A. (2005). “Energy consumption of asphalt and reinforced concrete pavement materials and construction.” *J. Infrastruct. Syst.*, 11(1), 9–20.

J. Transp. Eng. 2013.139:138-146.