Cold Regions Science and Technology 86 (2013) 104–112

Contents lists available at SciVerse ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Use of chloride-based ice control products for sustainable winter maintenance: A balanced perspective

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ARTICLE INFO

Article history:
Received 25 June 2012
Accepted 4 November 2012

Keywords:
Highway transportation
Systems engineering
Sustainable winter maintenance
Hidden costs
Asset management
Decision making

ABSTRACT

Drawing upon relevant literature, this work explores various dimensions of using chloride-based ice control products for winter maintenance operations. Winter maintenance operations play an important role in assuring the safety, mobility and productivity of roadways enduring wintery weather. Traditionally, nominal cost and effectiveness are the major criteria when highway professionals select the chemicals for snow and ice control. However, there are growing concerns over negative impacts that chloride-based ice control products pose on motor vehicles, the transportation infrastructure, and the environment. The authors propose that the use of chloride-based products for sustainable winter maintenance necessitates the application of a balanced perspective and collaborative decision-making among all relevant stakeholders. The shortcomings of existing maintenance decision systems are discussed, followed by a new way of thinking under the asset management framework.

1. Introduction

The last decades have seen steady increase in the use of chloride-based ice control products for winter maintenance operations, along with the awareness of associated environmental risks. It has become increasingly clear that the environmental cost associated with such products is a factor to be balanced with the value they provide. This is evidenced in a growing number of new initiatives to manage and limit deicer usage, such as the Transportation Association of Canada's Road Salt Management Guide, the Minnesota Pollution Control Agency's Metro Area Chloride Project, and the New Hampshire Road Salt Reduction Initiative. A recent National Cooperative Highway Research Program (NCHRP) report on "Grand Challenges: a Research Plan for Winter Maintenance" identified "balancing social, environmental and economic factors" as one of the six critical issues in advancing winter highway maintenance (Nixon WA and Associates, 2010). In light of the ever-increasing urbanization and customer demand for higher level of service (LOS) on winter roads, this issue is anticipated to be one of the greatest and most persistent challenges for the highway agencies in the coming years. In this context, there is a need to adopt sustainability principles to highway winter maintenance.

The definition of sustainability may vary depending on the specific system it is applied to. However, the principles of sustainability generally focus on integrating the multiple objectives in economic growth, social progress and ecological balance. The World Commission on Environment and Development (1987) defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Since then, the importance of sustainability has been widely accepted by various industries. The evolution towards sustainable operation management is clear in three areas: green product and process development, lean and green operation management, and remanufacturing and closed-loop supply chains (Kleindorfer et al., 2005). It is widely recognized that the principles of sustainability should guide all transportation design and operations. The U.S. Federal Highway Administration (FHWA) has developed a practical, web-based collection of best practices that would assist the state departments of transportation (DOTs) with integrating sustainability into their transportation system practices. And a FHWA tool entitled INVEST (Infrastructure Voluntary Evaluation Sustainability Tool, www.sustainablehighways.org) has included a segment on winter maintenance, detailing the implementation of standards of practice for snow and ice control, a road weather information system (RWIS), a materials management plan, and a maintenance decision support system (MDSS). Winter maintenance has surfaced as a critical area for transportation sustainability (Nixon, 2012; Nixon and Mark, 2012; Nixon et al., 2012).

When promoting sustainable winter road service, it is important to consider public perception. The general public often recognizes the need for and benefits of such operations, yet is concerned about the environmental risks associated with the use of chloride-based

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0165-232X/$ – see front matter
http://dx.doi.org/10.1016/j.coldregions.2012.11.001

products, traction sand, and other materials for snow and ice control. In the U.S., environmental issues related to water quality, air quality and wildlife are regulated with the guidance of the Clean Water Act, Clean Air Act, and Federal Endangered Species Act. These laws also detail the identification and management of environmentally sensitive areas, such as those on the list of impaired streams for water quality and the list of PM-10 non-attainment communities for air quality.

This work aims to summarize the existing knowledge relevant to the sustainable use of chloride-based products for snow and ice control on winter roads and presents a new way of thinking under the asset management framework. Currently, there is a lack of literature to support the asset management approach to winter maintenance. As such, this work will first discuss the state of the knowledge in highway winter maintenance, present some background information on the chloride-based ice control products, and then summarize the known benefits and negative impacts of using chloride-based products. Subsequently, the shortcomings of existing maintenance decision systems are discussed, followed by a discussion of the vision and challenges for snow and ice control asset management system.

2. Highway winter maintenance: state of the knowledge

In the northern United States, Canada and other cold-climate regions, snow and ice control operations are essential to ensure the safety, mobility and productivity of highways where the driving conditions are often worsened by inclement wintery weather. Chloride-based ice control products play a key role in such operations (Nixon and Williams, 2001). Chlorides can be found in a wide variety of snow and ice control products used on winter roadways to either prevent the bonding of ice to the roadway (anti-icing) or break the bond between ice and the roadway (deicing). The chlorides melt ice and snow by lowering the freezing point of the snow-salt mixture. Prior to application onto roadways, liquid salts can also be added to abrasives or solid salts to make them easier to manage, distribute, and stay on roadways (pre-wetting). For simplicity, this paper uses the term *deicer* to refer to all chemicals used for anti-icing, de-icing and pre-wetting operations.

Over the last two decades, maintenance departments in North America have gradually made two transitions in their snow and ice control strategies. First is the transition from the use of abrasives to the use of more chemicals (Staples et al., 2004).This is partially owing to the negative impact of abrasives (e.g., sand) to water quality and aquatic species, air quality, vegetation, and soil and the hidden cost of sanding (e.g., cleanup cost). In addition, the use of abrasives for winter maintenance has cost and environmental implications as it depletes valuable aggregate sources. Depending on its particle size, sand may contribute greatly to air pollution, can potentially cause serious lung disease, and is listed as a carcinogen (Fischel, 2001). Sand also poses significant risk for water quality and may threaten the survivability of aquatic species especially during spring runoff (Staples et al., 2004). Even after cleanup, 50 to 90% of the sand may remain somewhere in the environment (Parker, 1997).

In more recent years, there is increased adoption of anti-icing strategy by many highway agencies in the U.S. in place of deicing (O'Keefe and Shi, 2005). Defined as "the snow and ice control practice of preventing the formation or development of bonded snow and ice by timely applications of a chemical freezing-point depressant" (Ketcham et al., 1996), anti-icing has proven to be a successful method of maintaining roadways during the winter season. Relative to deicing and sanding, anti-icing leads to improved LOS, reduced need for chemicals, and associated cost savings and safety/mobility benefits (Blackburn et al., 2004; Conger, 2005). Anti-icing with liquid chemicals is more sensitive to weather conditions than other winter maintenance practices (Blackburn et al., 2004; O'Keefe and Shi, 2005). Near-real-time weather and road condition information and customized weather service are valuable to the success of such proactive maintenance strategies (Blackburn et al., 2004; Shi et al., 2007; Ye et al., 2009a). In practice, most agencies currently take a toolbox approach customized to their local snow and ice control needs as well as funding, staffing, and equipment constraints. Depending on the road weather scenarios, resources available and local rules of practice, agencies use a combination of tools for winter road maintenance and engage in activities ranging from anti-icing, deicing, sanding (including pre-wetting), to mechanical removal (e.g., snowplowing), and snow fencing.

Maintenance agencies are continually challenged to provide a high LOS and improve safety and mobility of winter roads in a cost-effective manner while minimizing corrosion and other adverse effects to the environment (Fay and Shi, 2012; Shi and Akin, 2012). To this end, it is desirable to use the most recent advances in the application of anti-icing and deicing materials (Fay and Shi, 2011), winter maintenance equipment and sensor technologies (Shi et al., 2006), and RWIS (Ballard et al., 2002) as well as other decision support systems (Ye et al., 2009b). Such best practices are expected to improve the effectiveness and efficiency of winter operations, to optimize material usage, and to reduce associated annual spending and corrosion and environmental impacts.

In the complex context of winter maintenance operations, sustainability may take many dimensions in the economic, social, and environmental domains and research is ongoing to define such details (Nixon, 2012). Nonetheless, sustainable winter maintenance should entail effective and efficient practices of using available resources to achieve an appropriate winter road LOS in an environmentally and fiscally responsible manner (Fay and Shi, 2011; Shi, 2010; Shi and Akin, 2012; Shi et al., 2009b). To "improve transportation safety and reliability and enhance winter hazard mitigation", best practices may be adopted in the areas of "road weather forecasting, anti-icing, snow and ice control equipment, and new (deicer/anti-icer) chemistry" (Smithson, 2012) and performance management (Qiu and Nixon, 2009).

The United States applies approximately 15 million tons of salts each year (Salt Institute, 2005) and spends \$2.3 billion annually to keep roads clear of snow and ice (Federal Highway Administration, 2005), which translates into average nominal cost of *\$153 per ton* for salting. This nominal cost considers the costs of materials, staffing and equipment. While snow and ice control activities are essential to maintaining winter roadway safety, mobility and productivity (Institute for Safety Analysis, 1976; Kuemmel and Hanbali, 1992), the use of chloride-based products has raised concerns over their negative impact on metallic components on motor vehicles (Dean et al., 2012; Shi and Akin, 2012; Shi et al., 2009c), the transportation infrastructure (Federal Highway Administration, 2002; Shi, 2008; Shi et al., 2009a, 2010a, 2010b, 2011), and the environment (Buckler and Granato, 1999; Fay and Shi, 2012; Levelton Consultants, 2007). One study published in 1992 estimated that chloride-based ice control products imposed infrastructure corrosion costs of at least \$615 per ton, vehicular corrosion costs of at least \$113 per ton, aesthetic costs of \$75 per ton if applied near environmentally sensitive areas, plus uncertain human health costs (Vitaliano, 1992). Arguably the cost of vehicular corrosion should have decreased since then, as vehicles today feature improved corrosion resistance via better design and materials selection.

3. Chloride-based products for snow and ice control

Chloride-based salts are the most common chemicals used to serve as freezing-point depressants for winter road maintenance applications. Sodium chloride (NaCl) is the most widely used chemical due to its abundance and low cost (Fischel, 2001). It can be used either as rock salt (for de-icing) or as salt brine (for anti-icing). However, it is rarely used and minimally effective below pavement temperatures of 10 °F (Transportation Research Board, 1991), i.e., −12 °C. Salt is also added to sand and other abrasives to prevent freezing. Calcium chloride ($CaCl_2$) or magnesium chloride ($MgCl_2$) is used by many DOTs in a brine solution for anti-icing, which exhibits better ice-melting performance than salt brine at cold temperatures (Baroga, 2003; Ketcham et al., 1996). The effective application temperature for $CaCl_2$, $MgCl_2$ and NaCl was reported to be −25 °C, −15 °C and −10 °C, respectively (Yehia and Tuan, 1998). $CaCl_2$ and $MgCl_2$ are more costly than salt, and they can be difficult to handle. At low relative humidity, their residue on roads can attract more moisture than salt, resulting in dangerous, slippery conditions under certain circumstances (Center for Watershed Protection, 2003). Field studies have shown $CaCl_2$ to be more effective than NaCl, owing to its ability to attract moisture and stay on the roads (Warrington, 1998). Granular $CaCl_2$ can be combined with salt to increase the effectiveness of salt in cold conditions, as calcium chloride acts quickly, gives off heat, and forms initial brine with moisture in the air (Wisconsin Transportation Information Center, 1996). However, some agencies choose not to use $CaCl_2$ as it does not dry and can cause roads to become slippery (Perchanok et al., 1991). Chlorides are generally considered the most corrosive winter maintenance chemicals (Shi et al., 2009b). Often, commercially available, corrosion-inhibited versions of these chemicals are used to reduce their deleterious impacts on vehicles and infrastructure.

In addition to chlorides, acetates such as potassium acetate (KAc) and calcium magnesium acetate (CMA) are used for anti-icing and they are generally much more expensive. However, KAc and CMA can be more effective, less corrosive to carbon steel, and not as environmentally harmful as chlorides (Shi et al., 2009b). Also available are a variety of agro-based chemicals used either alone or as additives for other winter maintenance chemicals (Nixon and Williams, 2001). Agro-based additives increase cost but may provide enhanced ice-melting capacity, reduce the deicer corrosivity, and/or last longer than standard chemicals when applied on roads (Fischel, 2001; Kahl, 2004). Both acetates and agro-based additives tend to increase the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in water bodies.

4. Benefits of using chloride-based products for winter maintenance

Highway winter maintenance activities can provide direct benefits to the public as they lead to fewer accidents, improved mobility, and reduced travel costs. They can also offer indirect benefits to the society and the maintenance agency, including reduction in liability claims, sustained economic activity, continued access to social activities, increased travel comfort and convenience, reduction in decision-maker stress, improved public perception of maintenance agency, etc. Welch et al. (1977), in discussing the economic impacts of snow on traffic delay and safety, identified different categories of benefits that accrued from different LOS, including vehicle operating cost savings, travel time savings, and accident reductions. This work also provided general figures illustrating the costs of driver discomfort by time and lost wages per worker based on tardiness. McBride developed an economic model that determined the economic benefits accrued by snow and ice control (McBride, 1977, 1978). It employed five modules that incorporated the maintenance, traffic and safety, environment, structural deterioration and vehicle corrosion aspects of winter maintenance. Consequently the model primarily produced benefit estimates via the maintenance module, where LOS goals, available material and equipment, requirements to achieve a specific LOS, traffic volume, highway type, and snow accumulation were used as input for cost analysis and comparisons. Using this information, probabilistic delay functions were developed to determine delays per volume of traffic, which were then converted to cost values by using comfort and convenience, vehicle costs and lost wage values. The difference (savings) between these costs for different LOS was the benefit for that particular maintenance operation. Haber and Limaye (1990) analyzed the benefits and costs associated with winter maintenance activities in Idaho. Among the benefits, those in decreased delay, increased comfort and reduced inconvenience were quantified by the researchers using stochastic simulation models to determine the impacts of changes in LOS on delay. Given that the values for each of the identified benefits varied by LOS, trip length, etc., no specific quantified values were cited by this study. According to a case study by Kuemmel and Hanbali (1992), during the first 2 h following maintenance, the direct road user benefits amounted to $6.50 for every $1.00 spent on two-lane highways and $3.50 for every $1.00 spent on freeways for maintenance. The direct costs of maintenance were offset once 71 vehicles and 280 vehicles had driven over a two-lane highway and freeway, respectively, with maintenance costs being paid for after approximately 35 min. A discussion paper by Environment Canada identified the direct and indirect benefits of using salt in winter maintenance and provided quantified values when available (in 2002 Canadian dollars) (Regulatory and Economic Analysis Branch, 2002). Direct benefits included the following: avoided fatalities, injuries and property damage — savings of $1,594,412 per fatality, $28,618 per injury and $5,724 per property damage crash eliminated; and fuel savings — 33% reduction, translating into savings of $1.88 per 100 kilometers traveled.

First of all, a major benefit item associated with highway winter maintenance operations is safety of the traveling public. A case study in 1992 showed that the costs related to traffic accidents decreased by 88 percent after application of deicing salts (Kuemmel and Hanbali, 1992). The researchers also found a significant reduction in crashes following salting operations, with an 87% reduction observed on two-lane undivided highways and a 78% reduction on freeways. A simple before-and-after approach was employed which estimated traffic volumes based on historical data rather than observed counts. Weather-related factors, as well as the use of other winter maintenance operations (e.g., plowing), were not considered, which calls into question the true contribution of salting to the observed crash reductions. For a 30-mile roadway segment in Iowa, accidents increased by 1300% and traffic volume decreased by 29% during severe winter weather events (Knapp et al., 2000). While this 30-mile segment is not representative of all winter roadways, the observations generally arrive at a similar trend of accidents increasing and average daily traffic volumes decreasing in the presence of snow and ice. In the State of Washington, it was found that 8% of the accidents that resulted in injury or fatality during a five-year period (1991 to 1996) occurred on snowy, icy roads (Boon and Cluett, 2002). For Washington State, it was found that "crash frequency in the presence of snow was five times higher than the rate under clear conditions". A comparison of crash rates between winter and summer revealed that January had 12 times the accidents as July (Goodwin, 2003). More recently, Fu et al. examined the effects of wintery weather and maintenance treatments on traveler safety (Fu et al, 2006). Daily accident data, weather conditions and maintenance operations data were examined for two provincial highways in Ontario, Canada. The researchers employed a Generalized Linear Model (GLM) to identify weather and maintenance factors that had a significant impact on crash frequency. It was found that anti-icing and pre-wetting operations improved safety on one study route (anti-icing was used on only one route), while sanding operations had a positive effect on safety on both routes. The researchers noted that the safety effect of plowing and salting operations could not be statistically confirmed by their work, noting that there could be inter-dependency between maintenance operations and snow conditions, with more maintenance operations dispatched during more severe weather conditions. Consequently, the variation in these operations under a given weather condition may have been small (Fu et al, 2006). This work offered a statistical approach to establishing the safety benefits of winter maintenance.

Secondly, another major benefit item associated with highway winter maintenance operations is improved mobility. In other words, by maintaining the highways at a reasonably high LOS, substantial benefits can be realized through reduction in road closures and congestion, travel time savings, etc. Morisugi et al. (2002) evaluated the benefits of snow removal in the Tohoku region of Japan. The researchers estimated generalized traffic savings based on comfort and punctuality metrics provided by different levels of maintenance operations. These were specified by using stated preference data from driver survey, and the data were examined using a logit model with a linear utility function. More recently, Shahdah and Fu conducted a simulation-based analysis to quantify the mobility benefits of winter maintenance using a freeway segment near Toronto, Ontario, Canada (Shahdah, 2009; Shahdah and Fu, 2010). A model was used to simulate traffic operations under a set of assumed snow storm events and maintenance scenarios. The researchers found that relative to the snow-covered scenario, perfect road maintenance producing bare, wet pavement during low snowfall events could save a total travel time of about 6 to 7% for volume/capacity (V/C) ratios from 0.35 to 0.60, 26 to 27% for V/C ratios of 0.70 to 0.75, and 10 to 11% for V/C ratios between 0.90 and 1.00. This travel time savings generally increased with snowfall intensity, with savings during heavy snowfall estimated to be between 7 to 11% for V/C ratios of 0.35 to 0.60, 29 to 36% for V/C ratios of 0.70 to 0.75 and 5 to 12% for V/C ratios of 0.90 and 1.00. While this work did not examine the impacts of specific winter maintenance practices in a real world setting, it still indicates that aggressive winter maintenance strategies result in improved operations.

Thirdly, highway winter maintenance operations can reduce the travel costs to road users. Fuel costs tend to increase with decreasing temperatures in wintery weather, due to slick roads and snow buildup on vehicles, especially around tires. Kuemmel and Hanbali (1992) performed a before-and-after analysis on the effectiveness of salting on vehicle operating savings and assumed that speed reductions of 10 mph on both two-lane highways and freeways resulted from weather. The researchers found that total direct operating costs for motorists fell from 7.3 cents to 6.1 cents per vehicle mile traveled on two-lane highways and 53.5 cents to 23.8 cents per vehicle mile traveled on freeways following maintenance activities. It is estimated that a short winter trip may consume 50% more fuel than the identical trip driven in the summer (Natural Resources of Canada, 2004). Some other studies in both Canada and US also show that winter driving requires 33% more fuel on average than the other seasons (Transportation Association of Canada, 2004).

Most importantly, the cost of shutting down the highways in severe wintery weather conditions is not affordable. Society has grown accustomed to year-round travel on “bare pavement” conditions, and the economy relies on it. The cost of road closure is far greater than the cost of highway winter maintenance activities. A 4-day blizzard shutdown in 1996 for much of the northeastern US led to about $10 billion lost in production, not including accidents, injuries or other associated costs (Salt Institute, 1999a). It was found that “failure to get snowplows out and salt on the roads during a single day of a winter storm costs almost three times more in lost wages than the total annual costs for snowfighting” (Salt Institute, 1999b). Thornes (2000) estimated that the benefits of winter maintenance to outweigh the costs by 8:1. Hanbali (1994) also claimed that direct benefits included vehicle operating cost reductions, travel time reductions, and avoidance of property damage, injuries and loss of lives; and indirect benefits included availability of community services (e.g., police, fire) and maintenance of business operations. Hanbali noted that many of the benefits that fall under these categories are intangible. Nonetheless, he concluded that maintenance operations produced a direct savings to road users of 45 cents per kilometer of travel on two-lane highways and 20 cents per kilometer of travel on multilane freeways.

5. Negative impacts of using chloride-based products for winter maintenance

Research has indicated that the detrimental environmental impacts of abrasives (such as sand) generally outweigh those of chlorides (Staples et al., 2004). In addition, the use of abrasives requires at least seven times more material to treat a given distance of roadway, compared with salt (Salt Institute, 2005). Therefore, a combination of salting and snowplowing is considered the best practice for snow and ice control.

Today's motor vehicles have a wide array of metals in them, e.g., steel, cast irons, aluminum alloys, magnesium alloys, and copper and copper alloys, all of which are subject to the corrosive effects of deicers. In addition to detrimental cosmetic effects of corrosion, chloride-based products may also lead to corrosion of critical vehicular parts such as brake linings, frames, and bumpers. A 1985–1990 field study in Sweden revealed that compared with those exposed to NaCl salted roads, the cars driven on unsalted roads had 50% less incidence of cosmetic corrosion and the carbon steel test panels had more than 90% reduction in corrosion rate (Rendahl and Hedlund, 1992). While manufacturers have increased the corrosion resistance of motor vehicles in the last two decades, the annual cost of corrosion in this sector is still substantial. As of 1999, there were more than 200 million registered motor vehicles on the United States' roadways, with a combined value of more than $1 trillion and annual corrosion cost of $23.4 billion (Johnson, 2002). A study published in 1991 (Menzies, 1991) examined the average depreciation of motor vehicles in different regions of the United States Automobiles in the North Atlantic region were compared with those in the Southern Atlantic and Gulf Coast regions in order to ignore corrosion due to marine environments and only investigate corrosion due to chloride-based ice control products. The study came to an estimate of $17 of additional corrosion damage per year for each vehicle in the Snowbelt region, where approximately 60% of the vehicles in the United States operate. Hence, the cost of vehicular corrosion damage due to chloride-based ice control products was estimated at $2.04 billion per year (60%×200 million×$17), which translates into *$136 per ton of chloride-based products*. Note that this estimate is relatively conservative, since the repairs and maintenance necessitated by corrosion are not accounted for. Otherwise, the corrosion of motor vehicles due to chloride-based ice control products would cost $2.8 billion to $5.6 billion per year (Menzies, 1992).

In addition, the corrosion damage of chloride-based ice control products to the transportation infrastructure (steel bridges, large span supported structures, parking garages, pavements, etc.) has enormous safety and economic implications (Shi et al., 2009c). Over five billion dollars are spent each year by state and local agencies to repair infrastructure damage caused by snow and ice control operations (Federal Highway Administration, 2005), which translates into *$333 per ton of chloride-based products*. As of 1999, there were 583,000 bridges in the United States, with approximately 15% of all bridges structurally deficient and annual corrosion cost of $8.3 billion. It is estimated that installing corrosion protection measures in new bridges and repairing old bridges could cost Snowbelt states between $250 million and $650 million per year (Transportation Research Board, 1991). Parking garages, pavements, roadside hardware, and non-highway objects near salt-treated roads are also exposed to the corrosive effects of chloride-based ice control products. Indirect costs to the user in traffic delays and lost productivity are estimated at more than ten times the direct cost of corrosion maintenance, repair, and rehabilitation (Yunovich et al., 2002). First of all, chloride ions from chloride-based ice control products can diffuse into concrete structures such as bridge decks and result in corrosion of the reinforcing steel (Shi et al., 2010b). A major cause of concrete deterioration (cracking, delamination, and spalling) is the corrosion of steel often initiated and promoted by chloride ions. In addition to marine environments and contaminated mix constituents, the chloride-based ice control products are a major source of these aggressive agents. The chloride diffusion coefficients for $MgCl_2$ are about two to three times greater than those of NaCl (Deja and Loj, 1999; Hondo et al., 1974; Mends and Carter, 2002), which may reduce the time to corrosion initiation for the concrete embedded reinforcing steel by 10 to 15 years (Mussato et al., 2004). In the

Snowbelt region, the synergism of freeze–thaw cycles and corrosion of rebar or dowel bar can lead to serious problems against reinforced concrete structures or pavements. The use of properly cured, air-entrained concrete can minimize the damage by freeze-thaw cycling, but chlorides can still penetrate and migrate through the concrete and cause the depassivation and corrosion of steel. The corrosion products lead to expansion in volume and build up tensile stresses in concrete, which can cause cracks and compromise the design strength of the structure. Second, chloride-based ice control products may pose a risk for the durability of concrete structures and pavements through three main pathways: (1) physical deterioration of the concrete through such effects as salt scaling (Hassan et al., 2002; Shi et al., 2010a); (2) chemical reactions between deicers and concrete (especially in the presence of Mg^{2+} and Ca^{2+}) (Darwin et al., 2007; Shi et al., 2011; Sutter et al., 2008); and (3) deicer aggravating aggregate–cement reactions (Rangaraju and Olek, 2007; Shi et al., 2009a). For instance, laboratory studies have also demonstrated that concentrated $MgCl_2$ deicers cause deterioration of mortar and concrete specimens (Cody et al., 1994, 1996; Kozikowski et al., 2007; Mussato et al., 2004). Finally, the deicer impacts on asphalt concrete pavements had been relatively mild until acetate- and formate-based deicers were introduced in recent years. The damaging mechanism seems to be a combination of chemical reactions, emulsifications and distillations, as well as the generation of additional stress in the asphalt concrete (Shi, 2008). A study in 2002 examined the effect of different deicers (salt, potassium acetate, sodium formate, and urea) on airfield asphalt concrete materials and mixes, and the presence of deicers was found to have a damaging effect on both the aggregates and the asphalt mixes (Hassan et al, 2002).

Finally, the environmental impacts of chloride-based ice control products have been a subject of research since their usage became widespread during the 1960s for highway maintenance (Hawkins, 1971; Paschka et al., 1999; Ramakrishna and Viraraghavan, 2005; Roth and Wall, 1976). For instance, increased salinity in adjacent waterways and soils, degradation of the environment along the roadside, and infiltration of cations (Na^+, Ca^{2+}, Mg^{2+}, etc.) and the chloride anion (Cl^-) into soils and drinking water are concerns associated with the use of chloride salts (Transportation Research Board, 1991). Abundant evidence demonstrates that chloride salts accumulate in aquatic systems (Kaushall et al., 2005; Mason et al., 1999), cause damage to terrestrial vegetation (Bryson and Barker, 2002; Public Sector Consultants, 1993), and alter the composition of plant communities (Miklovic and Galatowitsch, 2005). The use of chloride salts may liberate mercury and other heavy metals from lake sediments or soil through ion exchange processes (Jones et al., 1992). NaCl, $MgCl_2$, and $CaCl_2$ all contribute chloride to surrounding environments, which may have detrimental effects once reaching certain levels. Environment Canada reported that many woody plant species sensitive to salt had vanished from Canadian roadsides (Environment Canada, 2001). The environmental impacts of chloride-based ice control products are difficult to quantify in monetary terms, as they are site-specific and depend on a wide range of factors unique to each formulation and spatial and temporal factors of the location. A recent survey of winter maintenance practitioners found water quality to be of the greatest concern, with air quality, vegetation, endangered species, and subsurface well contamination also mentioned as highly relevant (Levelton Consultants, 2007). Note that roadway winter operations are only one source from which chlorides can enter the environment. Other industries (e.g., water softeners) and private-sector (e.g., malls and parking lots) winter operations introduce significant amount of chlorides as well.

Despite the potential damaging effects of chloride-based ice control products, their use can reduce the need for applying abrasives, and pose less threat to the surrounding vegetation, water bodies, aquatic biota, air quality, and wildlife (Fay and Shi, 2011). The use of such ice control products can also reduce the environmental footprint caused by traffic accidents associated with snowy or icy pavement. Since most chlorides are readily soluble in water and difficult to remove, there have been concerns over their effects on water quality. However, several studies have found that chloride concentrations in highway runoff are typically low enough that chloride is quickly diluted in receiving waters. Therefore, the impacts of chemical deicers on receiving waters may be negligible in many cases, depending on the type and designated use of the receiving water, and on the drainage system used to discharge the runoff (Turner-Fairbank Highway Research Center, 1999). Chloride also causes great concern if it reaches groundwater used as a source of drinking water. In a Washington DOT field evaluation, however, chloride levels in roadside soils, surface water and underlying groundwater were found to be generally low and well below any applicable regulatory standards or guidelines (Baroga, 2003). Deicers are relatively non-toxic to aquatic organisms with some concerns about NaCl and $CaCl_2$ (Cheng and Guthrie, 1998). A Colorado DOT study examined the impacts of $MgCl_2$ on several aquatic organisms and concluded that during the study period in 1997–98 $MgCl_2$ had a very limited potential to cause environmental damage more than twenty yards from the roadway (Lewis, 1999). A Michigan DOT study concluded that deicers could be toxic to aquatic organisms, but only in streams with very low flows and in wetlands and ponds with long turnover times. The negative impacts of chloride compounds are most likely to occur in areas of high deicer use, where roadway runoff is channeled directly to small water bodies (Public Sector Consultants, 1993).

6. Maintenance decision system shortcomings

Much progress has been made over the past two decades in the area of managing winter maintenance operations through various tools, including the development of MDSS (Nixon, 2009; Ye et al., 2009c), Automatic Vehicle Location Technology (Ye et al., 2012), cost-benefit tools (Fay et al., 2010), and Maintenance Management Systems (MMS). While these types of tools are capable of providing or assisting in the development of winter maintenance decisions, each has shortcomings. A summary of some of these shortcomings specific to winter maintenance is provided in Table 1. Given these shortcomings, there remains a need for a holistic approach that strives to achieve sustainability in winter maintenance operations.

In the absence of a unified approach to management, a number of issues must be addressed to develop a sustainable approach to winter maintenance operations. First is the absence of a comprehensive approach to assess the tradeoffs between maintenance alternatives. While the institutional knowledge and experience of maintenance managers can in some cases address this in an informal manner, the different variables that are present from storm to storm, material to material, and so forth cannot always be compensated for by this knowledge. Instead, recorded experience or data should be employed from multiple sources and management mechanisms in an integrated manner to select the correct materials to employ from storm to storm.

Second, existing mechanisms and tools do not comprehensively handle information pertaining to all aspects of winter maintenance in manner that can facilitate optimized decision making and resource allocation. While improvements have been made in this area in recent years, they remain fragmented and focused on singular aspects (e.g., the use of deicing alone as opposed to the use of deicing in combination with plowing). This is partly the result of the failure to completely understand the true, collective costs (and benefits) of winter maintenance activities. Consequently, informed decision making and resource allocation cannot occur until information related to the various costs and benefits of winter maintenance and how they interact are understood and capable of being incorporated into the overall management process.

Third, the data to support management systems and decision making is often disparate, both in format and location. For instance, some data is available through AVL (assuming the system is used by an agency), while other information is available via MDSS (again,

Table 1
Management decision tools, advantages and shortcomings.

Mechanism/tool	Managerial benefit(s)	Issues/shortcomings
MDSS	• Allows for data driven maintenance decisions • Provides tool for historical data recording	• Does not account for current location and supply of materials in use or availability of crews
Automatic Vehicle Location (AVL)	• Provides tool for historical data recording (routes, material quantities, etc.) • Provides real-time mechanism to identify route/treatment needs	• Does not directly account for current or forecast weather • While capable of tracking historical data, not necessarily equipped to analyze that data for future improvement
Cost-benefit tools	• Provide estimates of expected results, costs and savings from use of a specific operation, material or practice	• Focus on singular operation, material or practice • Some costs or benefits have not been quantified to date
MMS	• Organize allocation of labor, material and equipment resources	• Not optimized to consider current road and weather conditions or incorporate such information from sources such as MDSS

assuming its use). This data, while potentially of use to each system, may not be in a usable format or lacks a mechanism to feed into the opposite respective system or a mechanism within those systems themselves to make use of said data. In other cases, data may be kept in paper formats, rendering it useless to computerized systems. As a result of these types of issues, data cannot be used collectively in a larger decision making context by existing systems.

Finally, as the previous paragraph alluded to, the processing of available data (both real time and historical) to arrive at decisions on material use and other operations/practices are not typically available in an integrated manner. While approaches and tools are available to produce compartmentalized decisions, the mechanism to arrive at a comprehensive maintenance decision that accounts for multiple activities/materials/operations/conditions and other variables has not been developed. Furthermore, existing management systems used in winter operations are not designed to address these multiple considerations in a sustainable fashion.

Based on these issues, it is clear that a different approach to winter maintenance management, employing aspects of the asset management approach is needed. While the focus of this paper is on the decision to use different salts, such an approach is equally applicable to the wider arena of winter maintenance. The prospective approach should incorporate performance measures in order to facilitate continuous improvement. Such an approach would bring together data from various platforms, tools and approaches such as MDSS, AVL, etc. to arrive at winter maintenance decisions that achieve overall sustainability economically, environmentally and operationally, achieving optimal safety and mobility for the traveling public.

7. Asset management in highway maintenance programs

Successfully implementing a highway winter maintenance program requires appropriate selection of chemicals for snow and ice control, obtaining the right equipment, having well-trained staff, making informed decisions, and proper execution of strategies and tactics. Russ et al. (2007) developed a decision tree for liquid pretreatments for the Ohio DOT. The decision tree was designed to help maintenance supervisors consider a number of factors, including current road and weather conditions, the availability of maintenance personnel and the best treatment strategy. Relying on an established decision-making process can help maintenance professionals make timely and consistent decisions on a day-to-day basis. This is especially important for anti-icing which is sensitive to pavement temperature, dilution, and other factors (Blackburn et al., 2004). Furthermore, Fay and Shi (2010)developed a systematic approach to assist maintenance agencies in selecting or formulating their deicers, which integrates the information available pertinent to various aspects of deicers and incorporates agency priorities.

By definition (Federal Highway Administration, 1999), asset management is "a systematic process of maintaining, upgrading, and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organized, logical approach to decision-making". Transportation asset management features the following characteristics (Cambridge Systematics, 2002):

- Policy driven
- Performance based
- Considers alternatives or options
- Evaluates competing projects and services based on cost-effectiveness and anticipated impact on system performance
- Considers tradeoffs among programs
- Employs systematic, consistent business processes and decision criteria; and
- Make good use of information and analytic procedures.

In recent years, maintenance management systems (MMS) have evolved from tracking of maintenance activities and accomplishments to performance-based planning and resource allocation, embracing the concept of asset management. For instance, the Colorado DOT MMS features a performance-based budgeting tool that incorporates levels of service related to the condition of highway maintainable items and to levels of activity performance or responsiveness (Markow and Racosky, 2001). The Alaska DOT MMS features a geographic information system (GIS) platform that enables the Department to track assets spatially, conduct performance measure evaluations, and produce detailed information for planning, budgeting, and reporting purposes (Stickel, 2004).

8. Snow and Ice Control Asset Management System: vision and challenges

Some products for snow and ice control may cost less in regard to materials, labor and equipment, but cost more in the long run as a result of their corrosion and environmental impacts. A balanced perspective should be utilized to ensure that any cost savings of winter maintenance practices would not be at the price of deteriorated infrastructure, impaired environment, or jeopardized traveler safety. The authors argue that the use of chloride-based products for sustainable highway winter maintenance necessitates the application of collaborative decision-making among all relevant stakeholders. In this context, the framework of asset management could be adopted for highway winter maintenance programs at various levels.

Snow and Ice Control Asset Management Systems (SICAMS) are desirable for highway agencies, in order to rationalize the investments in snow and ice control services and to determine how and when to make investments that will improve safety and mobility and preserve the environment, infrastructures, and so on. The asset management framework offers a holistic solution to highway winter maintenance issues and embodies a set of principles to improve the performance monitoring, accountability, and decision-making process. It may also help reduce the potential risks by being proactive and environmentally responsible.

Fig. 1 shows an integrated, strategic, and interdisciplinary approach to highway winter maintenance operations, with its focus on snow

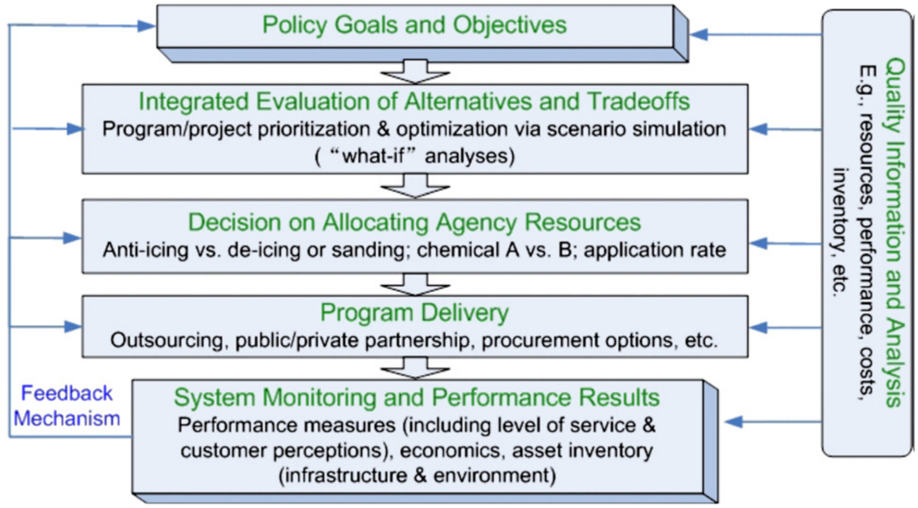

Fig. 1. A snow and ice control asset management system framework.

and ice control. It encourages such best practices as: policy-driven, customer-oriented, and performance-based planning; thorough evaluation of alternatives/available options; life-cycle cost analyses; systematic and consistent business processes and decision criteria; consideration of both nominal and hidden costs of snow and ice control.

Considerable amount of research is still needed in order to fill the knowledge gaps and establish a scientifically robust, defensible decision-making process for highway winter maintenance. To implement and sustain such a SICAMS system, a wide array of challenges remain in the following areas.

- *Available resources*: funding constraints by mode and function; fragmented responsibility across multiple agencies (Markow and Racosky, 2001); great variability in budget allocation, human resources, equipment and technologies over time, etc.
- *A comprehensive departmental data warehouse* (regarding financial, human and information resources, equipment, transportation infrastructure, traffic demand and forecasts, etc.): compounded by such issues as system integration, data integrity, accuracy, completeness, and currency (Markow and Racosky, 2001).
- *Asset data collection and classification*: to inventory in a tiered format the transportation infrastructure (highway bridges, pavements, roadside facilities, among others), surrounding environments (roadside vegetation and landscaping, water, air, wildlife, sensitive areas, etc.), motor vehicles (by user perception, etc.), and travelers (by average daily traffic and accident data). It is difficult to quantify the cost of environmental damage of chloride-based ice control products to soil, vegetation, surface and ground water, aquatic biota, wildlife, or human health and the damage is often site-specific.
- Integration of asset management information on a *GIS platform*: to visualize the project distribution, priorities, improvements over time, etc., and to integrate other sources of relevant information (such as capital programming).
- *Performance measures*: such as guideline compliance as a function of material usage, labor and equipment costs, etc., compounded by various weather severities across multiple winter seasons, improvements due to other practices and technologies, ever-improving levels of service, etc.
- *Institutional issues*: there is often a lack of coordination and integration among organizational units/stakeholders in snow and ice control operations. In light of the fact that the DOT organizational structure is hierarchical, it is difficult to promote effective communication and orchestrate actions across the different levels and units (such as bridge, pavement, maintenance, and environmental).

9. Conclusions

Drawing upon relevant literature, this work has explored various dimensions of using chloride-based ice control products for sustainable highway winter maintenance. Chloride-based products are widely applied for anti-icing, de-icing, and pre-wetting operations, all of which lead to substantial safety, mobility and other benefits to road users, maintenance agencies and society. Traditionally, nominal cost and effectiveness are the major criteria when highway professionals select the chemicals for snow and ice control. However, there are growing concerns over negative impacts that chloride-based ice control products pose on motor vehicles, the transportation infrastructure, and the environment. The corrosion and environmental costs pertinent to chloride-based ice control products amount up to at least $469 per ton on average, and they are often ignored in formulating highway winter maintenance strategies. The magnitude of such hidden costs is significant compared with the nominal cost of using chloride-based products for snow and ice control (approximately three times). The authors propose that the use of chloride-based products for sustainable highway winter maintenance necessitates the application of a balanced perspective and collaborative decision-making among all relevant stakeholders. In this context, the framework of asset management or other approaches could be adopted for highway winter maintenance programs with the goal of promoting sustainability in winter maintenance operations. The crux is to strike the right balance in meeting multiple goals of highway winter maintenance, including safety, mobility, environmental stewardship, infrastructure preservation, and economics. More concerted research efforts are needed to advance the relevant knowledge base and to promote the best practices of highway winter maintenance.

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