Sustainable Winter Road Operations
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Mobility is a critical part of modern society. Economies depend on the ability to move goods in a reliable and predictable manner and without this ability, economic output is severely degraded. People want to be able to move freely and thus require an effective and efficient transportation infrastructure to do so. Unfortunately, weather sometimes impacts the transportation system in such a way that it does not provide mobility and safety for goods and the traveling public. Transportation agencies, who are tasked with providing safety and mobility on the transportation system, thus undertake a variety of operations to maintain the safety and mobility of the transportation system even when the weather is less than ideal.

The economic impacts of a snow storm can be substantial. A variety of studies have considered the economic impacts of roads being closed (by, for example, a winter storm) across a state, and indicate that the economic cost of such a closure are between $300 and $700 million per day. And each year winter weather is a factor in crashes killing about 1,300 people. So good winter maintenance can clearly play an important role in providing safety and mobility for the traveling public.

This book aims to collect in one place all the information and understanding pertinent to conducting operations intended to ensure safety and mobility on the transportation system when that system is impacted by winter weather of all types. This foreword attempts to set this information and understanding in some sort of broad-brush context. Obviously, the details are in the main chapters of the book itself. The foreword is an enticement to dip into the chapters!

Over the past thirty years there have been significant advances in the practice of winter operations, and in our understanding of how those practices can be made more effective. A key part of this advancement has been the understanding, which has grown in the past decade, that the practice of winter operations not only has to be sustainable, but has to be seen to be sustainable. For the most part, those involved in the practice of winter operations have inevitably balanced societal, economic, and environmental needs. The goals of winter operations almost require that such a balance be sought after and achieved. However, while the practice has been sustainable, the language describing that practice has been less so. It is important that both the practice and the language of the practice be seen to be grounded in sustainable processes.
Given the focus of this text on sustainability it is important to consider what exactly sustainability means and how applicable it is to winter maintenance. The standard definition of sustainable practices is as follows:

Sustainable operations meet the needs of the present without compromising the ability of future generations to meet their own needs.

Unfortunately, this is not particularly helpful when it comes to winter maintenance operations. For example, snow plows are not mentioned at all! The definition does not touch upon some of the very important research done on materials we use in winter maintenance, such as NCHRP Report 577. And quite frankly, the definition is sufficiently vague that it could mean almost anything depending on what you want it to mean. For example, what do we mean by “needs?” And what will “compromise the ability of future generations?” The danger with the vagueness is that not only does it lack guidance but it allows interpretation that can vary hugely.

One particular aspect of sustainability that is especially pertinent to winter operations is the so-called triple bottom line. This approach suggests that rather than simply consider cost as the driving concern in operations, we should also consider societal needs and environmental impacts as having, if not equal weight, a similar weight in importance to budgetary concerns. In our field societal concerns relate to providing safety and mobility for the traveling public. Our environmental concerns relate to minimizing impacts on the environment. The latter is interesting because while, for example, using materials such as road salt does create a loading on the environment, so too does NOT using road salt. We know from a variety of studies that a well-designed and implemented winter maintenance operations program will reduce crashes by between 85 and 90%. And each and every crash is a small-scale environmental disaster – not only will various liquids (gasoline, diesel, engine oil, coolants and so forth) be spilled, but we will also have to replace the vehicles involved (not all the time, but it seems that even a small-scale crash can lead to a vehicle being written off), which carries material and energy costs with their own environmental issues. So, good environmental stewardship may require us to use road salt (in suitable amounts and under the correct conditions).

Another aspect of sustainability that is not captured by the standard definition is what I call the “one size does NOT fit all” consideration. Not every community has the same needs and expectations when it comes to winter maintenance. Not every agency needs to plow residential streets for example. Many cities and towns in Colorado do not plow residential streets unless there is a large snow accumulation (in some cases, as much as ten inches) because in most winter events the snow is melted by the following day. It is a truism that the weather is different all across North America, so having the same approach to winter maintenance in Toronto and in Atlanta does not make much sense.

This book deals with the various aspects of winter maintenance operations and of course does so on a chapter-by-chapter basis. While each chapter is to some degree a stand-alone document, it is not the intent of the book to suggest that there is no interaction between the various issues addressed within. Another aspect of sustainability when it comes to operations is to recognize that operations are part of a system and that each
part of the system can impact other parts. Thus, by way of a simple example, the weather forecast should impact material application rates, but so too should the current pavement condition, and the traffic levels on a given segment of road. If the book becomes a collection of “silos” of knowledge, it will have not succeeded in its aims.

In conclusion, winter maintenance operations are critical to the safety and mobility of our transportation systems. Equally, those operations must be conducted in a safe and sustainable manner. This book aims to detail how such operations can be conducted in such a way.
1

Introduction to Sustainable Winter Road Maintenance

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1.1 Introduction

1.1.1 Motivation for This Book

This book is motivated by the opportunities made possible by leveraging recent advances and significant knowledge accumulated in various aspects related to winter road maintenance (WRM), such as weather forecasting, sensor and equipment technologies, operational practices and materials, and performance measurement, to achieve sustainable winter operations. These opportunities enable new perspectives on and holistic approaches to achieving sustainability of WRM operations by minimizing physical and chemical impacts, economic costs, and societal vulnerabilities and risks of winter storms, and maximizing the synergies across multiple modes and jurisdictions.

Investing in WRM operations is essential and beneficial to the public and the economy. In many northerly countries and regions, WRM operations are essential to ensure the safety, mobility and productivity of transportation systems. The U.S. economy cannot afford the cost of shutting down the transportation system, such as highways and airports, during wintry weather. According to the U.S. Federal Highway Administration (FHWA), “over 70 percent of the nation's roads are located in snowy regions, which receive more than five inches average snowfall annually ... Nearly 70 percent of the U.S. population lives in these snowy regions” (Figure 1.1). Transportation agencies are under increasing pressure to provide a high level of service (LOS) and to improve safety and mobility in a fiscally and environmentally responsible manner. It is therefore desirable to be able to make full use of best practices in the application of materials, strategies, equipment and other technologies. 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. As described in Nixon \textit{et al.} (2012), WRM operations include six interrelated components and processes where improvements for sustainability can be made, as illustrated in Figure 1.2.
Figure 1.1 U.S. areas affected by snow and ice (Adapted from: FHWA 2016).

Figure 1.2 Key components and processes in winter transportation operations (Adapted from: Nixon et al. 2012).
WRM operations can greatly contribute to a safe and efficient transportation system and thus facilitate economic development by reducing logistics costs of firms and individuals. The U.S. alone spends $2.3 billion annually to keep highways clear of snow and ice, with another $5 billion estimated damage to the transportation infrastructure and natural environment (FHWA 2005). WRM operations have lasting economic, social and environmental impacts. They offer such benefits to the public and society as: fewer accidents, improved mobility, reduced travel costs, reduced fuel usage, sustained economic productivity, continued emergency services, etc. (Figure 1.3). An example of a winter storm hindering the U.S. economy occurred in 1996 when a blizzard shut down much of the northeastern U.S. for four days. The loss in production and in sales was estimated to be approximately $10 billion and $7 billion, respectively, without taking account of accidents, injuries or other associated costs (Salt Institute, 1999). A recent study for the National Research Council estimated the quantifiable benefits of winter highway maintenance by the Minnesota Department of Transportation (DOT) to be about $220 million per winter season, even without considering the risk of highway closures in the absence of winter operations (Ye et al. 2013).

Figure 1.3 WRM operations are vital to economy and society.
Sustainability in WRM operations has become a growing consideration over the past decade. Since a consensus has been reached that the principles of sustainability should guide all transportation design and operations, a variety of efforts have been conducted to follow this recognition. The U.S. FHWA has developed a practical, web-based collection of best practices that would assist state Departments of Transportation (DOTs) with integrating sustainability into their transportation system practices. Winter maintenance has emerged as a critical area for transportation sustainability (Nixon 2012; Nixon and Mark 2012; Nixon et al. 2012; Shi et al. 2013).

1.1.2 The Need for This Book

Winter road maintenance has always been an integral part of transportation operations for agencies that must deal with the impacts of adverse winter weather. Significant advances have been made in the various aspects of WRM operations, such as deicing/anti-icing materials, maintenance practices, equipment, and road weather and surface-condition monitoring. Most of these developments have been motivated by the need to provide a high level of service (LOS) and improve safety and mobility in a sustainable manner. However, currently there are no professional societies or scientific journals or textbooks dedicated solely to sustainable winter road operations and the key information is scattered across a variety of disciplines and in various forms of publications. As more agencies are exploring the impacts of WRM operations, including voluntary and regulatory controls to reduce their impacts, the development of a comprehensive book is timely to consolidate best practices and recent advances in sustainable WRM operations and to help reduce the cost and environmental footprint associated with WRM operations.

In this context, this book aims to bridge a significant knowledge gap and to address the pressing need for such a book for both education and workforce development. It will be the first book to provide a holistic perspective on the benefits and potential negative impacts of WRM operations while promoting environmental sustainability concepts and practices. This book will serve as essential reading for maintenance professionals in charge of snow and ice control operations on highways, local roads, etc. It will also serve as a textbook for senior elective or graduate-level courses, with outstanding potential for online education. Webinars and training modules could be developed using this book as the blueprint.

1.2 How the Chapters and Topics Are Organized

Following this introductory chapter, the rest of the book tackles the multiple dimensions of sustainable WRM operations. The individual chapters, while covering different topics related to WRM, are interrelated, with some serving as input to the others, as schematically illustrated in Figure 1.4. Chapter 2 provides a framework for assessing the life-cycle sustainability of salt application in winter maintenance operations. The framework integrates the triple bottom line of sustainability, i.e., economics, environmental stewardship and social progress in accounting for the direct and indirect costs, benefits and impacts over the entire life cycle of road salt. Chapter 3 provides a historical perspective detailing the important developments and evolutions in
materials, maintenance strategies, and equipment over the past three decades in advancing sustainable WRM operations. Chapter 4 discusses the societal and user expectations of WRM operations, as well as how agencies establish their LOS standards.

Chapter 5 provides an overview on how road weather services can greatly contribute to sustainable WRM operations. Chapter 6 discusses the fundamentals of plowing, anti-icing, deicing, and sanding operations, laying out the foundation for developing ways to improve the performance and sustainability of various maintenance treatments. Chapter 7 and Chapter 8 provide an overview of the methodologies that can be applied to understanding and quantifying the effects of winter weather and maintenance operations on road safety and mobility, respectively. Chapter 9 discusses the economic benefits of WRM operations and examines how they can be used in cost-benefit analysis of maintenance policies, programs and technology investment. Chapter 10 provides an overview of the environmental risks that some commonly used deicing/anti-icing materials may pose. Chapter 11 and Chapter 12 discuss the risks of WRM operations to the transportation infrastructure and motor vehicles, respectively, as well as the corresponding best practices to manage such risks.

Chapter 13 focuses on planning and management strategies for achieving sustainable WRM, such as network partitioning or districting, fleet sizing and mixing, siting of RWIS stations, and salt management. Chapter 14 discusses sustainability practices in the domain of source control tactics, including innovative snow fences for drift control, anti-icing, deicing and pre-wetting practices, maintenance decision support systems (MDSS), fixed automated spray technology (FAST), equipment maintenance and calibration, advanced snowplows and spreaders, and material and snow storage.
Chapter 15 discusses reactive approaches to reducing the environmental impacts of snow and ice control materials after their application on pavement. Chapter 16 focuses on the decision-making process for selecting the appropriate types of innovative equipment for WRM. Chapter 17 discusses the search for “greener” materials for WRM operations, with a focus on the development and evaluation of deicers. Chapter 18 provides an overview of pavement innovations that can reduce the need for chemicals or abrasives for WRM operations.

Chapter 19 describes the benefit of performance measurement in responsible and sustainable winter maintenance management, an overview of common performance measures, and how to overcome the challenges associated with analyzing winter operations performance. Chapter 20 presents a review of current snow and ice control methods and a guide for selecting an optimal application rate for specific weather, treatment and LOS requirements. Chapter 21 concludes the book with a look into the future in terms of the main challenges and opportunities and future research and development in sustainable WRM operations.

References


2

A Framework for Life-Cycle Sustainability Assessment of Road Salt Used in Winter Maintenance Operations

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2.1 Introduction

One of the basic requirements for successful implementation of a winter road maintenance (WRM) program is the appropriate selection of deicers (Shi et al., 2013). Traditionally, nominal cost and effectiveness are the major criteria used by roadway professionals when making such selection. However, there is growing concern over the negative impacts of such chemicals on the natural environment (Levelton Consultants, 2007; Corsi et al., 2010; Fay and Shi, 2012), transportation infrastructure (Pan et al., 2008; Shi et al., 2010; Xie et al., 2016), and motor vehicles (Shi et al., 2009; Dean et al., 2012). To tackle these risks, some endeavors have been made to find alternatives to regular road salt, e.g., agro-based and complex chlorides/minerals-based products (Hossain et al., 2015; Muthumani and Shi, 2016). These have triggered the need to adopt sustainability principles for WRM operations, so as to ensure that any cost savings of winter maintenance practices would not be at the expense of deteriorated infrastructure, impaired environment, or jeopardized traveler safety.

The principles of sustainability generally put emphasis on the “triple bottom line”: economy, environment and society, and these have yet to be applied to WRM operations. Over the past decade, addressing sustainability in WRM operations has attracted more attention (Nixon, 2012). To assess the life-cycle sustainability of chloride-based deicers for WRM operations, it is not sufficient to estimate only the economic savings from enhanced winter roadway safety and mobility; the indirect costs and benefits associated with infrastructure degradation, vehicle corrosion, etc. must also be investigated. Furthermore, efforts should be made to quantify the life-cycle footprint of each deicer for the natural environment and for society. It should be cautioned that many of the items regarding costs (or benefits), environmental impacts, and social impacts can be intangible, hard to quantify, and inherently stochastic, making it difficult to conduct a reliable life-cycle sustainability assessment (LCSA).
Since a consensus has been reached that the principles of sustainability should guide all transportation designs and operations, a variety of relevant efforts have been made towards adopting them in WRM operations. An example is the development of a practical, web-based collection of best practices by the U.S. Federal Highway Administration (FHWA), aimed to assist state departments of transportation (DOTs) with integrating sustainability into their practices in managing the transportation system. A FHWA tool, INVEST (Infrastructure Voluntary Evaluation Sustainability Tool), provides a segment on winter maintenance, including a road weather information system (RWIS), a materials management plan, and a maintenance decision support system (MDSS), and shows the implementation of standards of practice for snow and ice control (Shi et al., 2013). These endeavors have been useful in promoting sustainability in WRM operations, but do not provide any framework to enable reliable quantification of life-cycle sustainability of deicers or other WRM practices.

The multiple dimensions of deicer selection demand an integrated sustainability assessment framework, which is currently non-existent in the published literature. Yet this framework is much needed by agencies so that they can appropriately assess the related social–economic costs and benefits of a deicer and comprehensively account for its environmental impacts, and thus make more informed decisions based on comparisons of different deicer products and improve their operations (Fitch et al., 2013). For instance, depending on the design and manufacturing technique of products used for snow and ice control, the mining, production, distribution, storage, and application of these compounds unavoidably contribute to the environmental footprint of WRM operations. The negative impacts of deicers on vehicles and infrastructure also induce secondary environmental impacts. As such, it is important to consider the entire life cycle of deicers, from mining/extraction, processing, storage, distribution, roadway application to eventual fate and transport in the environment, or recycling. These considerations should be examined with a life-cycle approach and a balanced perspective among all relevant stakeholders.

A LCSA framework would help produce a full picture of the impacts of each step in the use of deicers and thus facilitate more balanced decisions. As such, this chapter anatomizes the LCSA framework of road salt (the most commonly used deicer for anti-icing, deicing and pre-wetting practices), through analyses based on the triple bottom line. This reflects the current state of thinking on the structure of the LCSA framework for road salt, including concepts, complexities and caveats, and considerations in each of the three branches of LCSA (economic, environmental, and social aspects). While this framework is the first step in the right direction, we envision that it will be improved and enriched by continued research and may serve as a template for the LCSA of other WRM products, technologies, and practices.

### 2.2 Concepts of LCSA

 LCSA represents a new philosophy that has been widely discussed in recent years (Zamagni, 2012). Based on the definition in the context of sustainable development, the “triple bottom line” or the “three pillars” mode forms the basis of expression for LCSA in its measurement. This can be overly simplified as a linear equation (2.1) as follows.

\[
\text{LCSA} = \text{LCC} + \text{LCA} + \text{SLCA}
\]

(2.1)
where LCC, LCA, and SLCA denote life-cycle costing, environmental life-cycle assessment, and societal life-cycle assessment, respectively. They respond to the economic, environmental, and societal aspects of sustainability assessment, respectively, and jointly constitute the systematic structure of LCSA (Zamagni, 2012; Kloepffer, 2008).

LCC works to capture the economic effects of an industrial product or activity throughout its life-cycle stages. Usually it starts from calculating the direct cost, from extraction of resources, to production and usage of the product, to the cost management of product reuse, recycling, and disposal. Benefit accrued during any of the life-cycle stages can be considered a negative cost. Woodward defined the life-cycle cost of an industrial product or activity as: “the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life” (Woodward, 1997). Harvey (1976) proposed a general LCC procedure, summarized in Figure 2.1, in which the step “Define the cost elements of interest” entails the estimation of the direct cost that occurs during the service life of an industrial product or activity; “Define the cost structure to be used” entails the grouping of costs to identify potential trade-offs in the optimization of LCC; “Establish the cost-estimating relationships” entails a mathematical expression that estimates the cost of an industrial product or activity as a function of different variables; and “Establish the method of LCC formulation” entails the process to finalize an appropriate approach to evaluate the life-cycle cost of an industrial product or activity.

LCA was developed as an analytical tool to assess the environmental impacts of an industrial product or activity. The International Standards Organization (ISO) initiated a global standardization process for LCA, including the development of four standards (goal and scope definition, inventory analysis, impact assessment, and interpretation), as well as a definition and basic requirements, as shown in Figure 2.2. In the ISO 14040 standard, LCA was defined as “the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle” (Guinee et al., 2002). The typical environmental impact categories include: energy consumption; resource use; emissions (related to climate change, ozone layer depletion, acidification, eutrophication, etc.); toxicity; water; and waste.

SLCA focuses on the social impacts of an industrial product or activity, specifically on the societal aspect of life-cycle sustainability (Jørgenen et al., 2010). SLCA differs from its precursor, Social Impact Assessment (SIA). Even though SIA also aims to examine the social impacts of industrial products or activities, impacts across a whole life cycle are generally not included in its analysis. In contrast, SLCA can be defined as an aggregation of all phases of SIA in a product’s life cycle (Fan et al., 2015). With a research focus on the effects of activities on humans, SLCA faces a major challenge in how to quantify the social impacts of the particular system under assessment. Dreyer et al. (2006) presented an SLCA approach to standardize and quantify the social impacts as
specific numbers by using scorecards, and later further improved it with more details and specifics for social issues and location. However, the method requires site-specific data that may not be readily accessible. Jorgensen et al. (2012) considered the most important part of SLCA to be the obtaining of available data and recommended conducting the SLCA with generic data, such as those from national censuses or public surveys. In 2006, a series of socioeconomic indicators were introduced for the application of SLCA, including human rights, labor practices, decent working conditions, and
product responsibilities. These factors are directly affiliated with a stakeholder of the corresponding product (Grießhammer et al., 2006). The indicators affiliated with the stakeholders in the life cycle of a product or activity tend to provide the assessment of midpoint (e.g., worker, consumer, local community, society, and value chain actors shown in Figure 2.3).

In light of the working procedures and impacts of using road salt in WRM operations, it can be found that the three branches mentioned above are all embodied in WRM activities and are interrelated. The next section thus will provide a brief discussion on the complexities and caveats in the LCSA of road salt, aimed at helping agencies achieve the goal of life-cycle sustainability assessment from economic, environmental, and social aspects.

2.3 Complexities and Caveats in the LCSA of Road Salt

Currently there are considerable challenges in the quantification or estimation of the performance and impact of road salt in a given region and comprehensive LCSA of road salt is needed for informed decision-making. Where appropriate, necessary assumptions usually have to be made in order to bridge the knowledge gaps that currently exist in certain aspects related to the economic, environmental, and social impacts of road salt application. The potential sources of such complexities in the LCSA study of road salt (or other snow and ice control products) may include, but are not limited to, the issues discussed as follows.

First, there are indirect implications in terms of the environmental footprints, costs, or benefits of road salt, which can be considered “ripple effects”. This raises the need to define the boundary and time scale of the analysis domain and select the appropriate temporal and spatial resolution for the LCSA study. For instance, the application of road salt on winter pavement can induce higher risk of premature failure of concrete bridge decks, asphalt pavements, and motor vehicles, leading to the need for more frequent rehabilitation or repair activities and related traffic congestion. This, in turn, would induce a larger environmental footprint in terms of energy consumption, resource use, emissions, water pollution, etc., as well as indirect or secondary costs. To facilitate the LCSA, it is necessary to define the boundary of the analysis so as to focus on the major considerations. In addition, chlorides are known to be conservative in the environment. The application of road salt in many scenarios may pose little risk to the adjacent water bodies due to low acute concentrations observed, but pose significant risk to the water bodies over the longer term (e.g., accumulation over decades). It is thus necessary to define the time scale of the analysis so as to facilitate the impact assessment.

Second, the costs, performances, and impacts of road salt application can be regionalized, localized, or site-specific, whereas the current LCSA typically adopts general values which overly simplify them. For example, numerous studies have reported environmental risks of deicers, indicating that the actual effects are highly site-specific and depend on the density of road networks; climatic, soil, hydrological, and vegetation characteristics of the site; type and amount of product applied, etc. (Fay and Shi, 2012). Thus there is always a lack of reliable data for quantitative studies. Even though available data could be adopted either from laboratory and field testing or from historical records and literature review, they may not be applicable for individual site conditions.
Third, many of the processes underlying the costs, performances, and impacts of road salt application are stochastic in nature, whereas current approaches for assessment are typically deterministic. For instance, the effect of salt-laden stormwater runoff from roads on the adjacent river or stream is partly affected by the flow rate and precipitation of the current and subsequent time periods. The fate and transport of sodium chloride and other additives in the road salt can be very complicated, in light of the inherently site-specific and stochastic nature of the underlying processes and their interactions. In other words, there is no universal or deterministic model that can be employed to reliably predict the level of the impacts posed by the road salt on the receiving roadside soil, water bodies, aquatic biota, and vegetation, and on human health.

Finally, the fate and transport of road salt in the environment and how salt deteriorates the natural environment and assets are poorly understood, let alone the quantification of costs and risks. There remains a lack of effective correlation between the data obtained from current laboratory methods employed to assess the environmental impacts of deicers (e.g., aquatic toxicity of road salt) and their actual field impacts.

These complexities and caveats in the LCSA study of road salt illustrate the challenges of addressing such sustainability assessment. As such, the next section presents a preliminary LCSA framework of road salt, which serves as a first step in the direction of decomposing the complexities, summarizing the key factors, and establishing a framework for further improvements.

2.4 A Preliminary LCSA Framework of Road Salt

This section provides a detailed anatomy of the LCC, LCA, and SLCA branches in the integrated LCSA framework for the road salt used in WRM operations. We place the focus on factors, components, and actions that should be considered in each branch, as well as on the relationships between these concepts in the LCSA system.

2.4.1 LCC Framework

The LCC framework of road salt considers the following factors and components: capital and annual costs, disposal cost, life of assets, and discount rate, for the time period under analysis. The costs may include those to the roadway agency and those to the roadway users. Once the expenditure stream is developed as a function of time, the net present value or annualized value of the road salt for snow and ice control can be calculated. The LCC can take either a deterministic or probabilistic approach, the latter of which is a more realistic representation of the actual situation. This is because most of the input factors for LCC feature some level of uncertainty and would be better characterized by a statistical distribution than a single value.

Generally the capital and annual costs include the costs of mining/manufacturing and storage (e.g., raw material extraction, land use, anti-caking treatment, ventilation, and packaging), transportation (e.g., from factory to DOT salt storage shed), implementation (e.g., application of road salt for anti-icing, deicing or pre-wetting practice), training (e.g., for the staff managing, handling and applying the road salt), equipment, and labor. Note that the benefits accrued from the application of road salt in terms of improved
traveler safety and mobility, reduced travel cost and fuel savings (Ye et al., 2013; Usman et al., 2012; Shahdah and Fu, 2010) can be considered as negative costs under the implementation category.

Disposal cost usually does not occur until the end of the service life of the assets. For the LCC of road salt, the disposal cost of the salt itself is typically negligible since the salt is typically not recovered from the environment once it is applied onto the pavement for snow and ice control. Instead, the disposal cost of motor vehicles and transportation infrastructure may be considered in the LCC framework, and so it is the life of these assets which is affected by their exposure to the road salt. The disposal cost may include the costs of demolishing, transportation (to the disposal site), landfill, and labor, and could be minimized with best practices in recycling repurposing, or reuse of the materials.

For LCC, the dollar values of all the cost and benefit components occurring in future years should be expressed in terms of current year dollars, i.e., present value. For analysis of costs and benefits directly or indirectly related to road salt, the discount rate could be considered within the range of 3% to over 20%, depending on the market needs and supplies, organizations, and technologies.

2.4.2 LCA Framework

Drawing upon the published literature, environmental LCA can be iteratively described by the following four categories: goal and scope definition, life-cycle inventory analysis, impact assessment, and interpretation.

Goal and Scope
For road salt, the goal of its LCA is to account for the negative impacts its life cycle may pose to the natural environment, including surface water, groundwater, air, soil, vegetation, wildlife, etc. As such, the results of LCA can be used to aid best practices by agencies to minimize negative environmental footprints and to address environmental justice and ecological issues.

In terms of scope or domain of analysis, the LCA aims to consider both the direct impacts of road salt on the receiving environment and the indirect environmental impacts (e.g., those induced by the premature failure of corroded equipment or transportation infrastructure). The environmental benefits derived from the use of road salt will be considered as well, including those from the avoidance of traffic accidents and delays, translated to reduced emissions and fuel consumptions (Min, 2015). It is cautioned that the scope can vary greatly as a function of time duration, geographic location, local priorities of environmental stewardship, technological context of salt application and infrastructure preservation, and possibly political and cultural constraints. As such, it is necessary to clearly define the scope of LCA before comparing different alternatives or different studies against each other.

Life-Cycle Inventory (LCI)
LCI is a process employed to define the inputs and outputs of an industrial product or activity interacting with the environment, and to collect data regarding the resultant environmental burden (ISO, 1998). The inputs of road salt in the LCI analysis mainly include the raw materials and energy consumed during the course of mining, manufacturing, storage, transportation, implementation, and disposal. The raw materials may
include not only the sodium chloride mineral and other additives in the road salt for WRM, but also the materials for preservation or rehabilitation of transportation infrastructure and the salt remover, anticorrosion coating, or corrosion inhibitor for equipment preservation. The outputs may include greenhouse gas emissions and other airborne pollutants, solid wastes (e.g., deteriorated vehicle parts, asphalt pavement, and concrete bridge deck), traffic noise (due to salt-deteriorated ridability of pavement surface), and liquid effluents (e.g., salt-laden stormwater runoff) discharged into the receiving environment.

Life-Cycle Impact Assessment (LCIA)
LCIA works to translate LCI results into potential environmental impacts, and the major concerns include human health, natural environment, natural resources, and manmade environment (Hauschild et al., 2005). The widely accepted four steps of LCIA include: the selection of impact categories and classification, characterization, normalization, and valuation (ISO, 2000). For road salt, the main environmental impact categories include: acute and chronic toxicity of sodium chloride and other additives to aquatic species and human beings; air/soil/vegetation/water pollution due to application of road salt; air/soil/vegetation/water and noise pollution due to increased preservation or rehabilitation activities of transportation infrastructure; chronic deterioration of wildlife habitat; greenhouse gas emissions (a.k.a., global warming potential); energy consumption; and solid waste. During the characterization step, the environmental impact in each category is quantified into scores or equivalent values (e.g., converting the greenhouse gas emissions into kg CO2 equivalents). The quantification of the environmental impacts can be highly variable and stochastic, depending on the geographical location, salt application process, and characteristics of the receiving environment. During the normalization step, the magnitude of these impact scores is normalized to the same scale that is applied to all the impact categories. During the valuation step, the relative importance of impact scores is evaluated by ranking or weighting factors.

Interpretation
The results of interpretation can help agencies understand the potential negative effects of road salt on the receiving environment and make more environmentally conscious decisions in light of the local priorities and constraints. It can also provide support to optimize the previous three categories in an iterative process to revise the goal and scope, LCI, and LCIA until a final decision can be made, as shown in Figure 2.2.

2.4.3 SLCA Framework
The SLCA framework of road salt considers both the positive and negative impacts of using road salt for WRM operations. On the positive side, there are societal benefits of road salt in terms of avoided traffic accidents and improved convenience due to the improved level of service on winter pavement. While difficult to monetize, the improved convenience may be realized in the form of continued community services, reduced response time to emergencies, reduced traveler discomfort, and reduced wage loss associated with absence from work. Other societal benefits may include increased worker opportunities, technology development, etc. listed in Figure 2.3.

On the negative side, there are societal implications of using road salt, in terms of increased risk to human health; inconvenience associated with increased inspection
and rehabilitation of motor vehicles, equipment, and roadway infrastructure; and possible increase in social inequality. First, there have been exceedances of the EPA water standard for chloride reportedly attributable to the use of road salt (Trowbridge et al., 2010). The conservative nature of sodium and chloride ions in the natural environment makes it difficult to remove them. Their concentration peaks during runoff or accumulation over the long term, along with their possible role in leaching other metals out of soil, can pose a health risk to human beings. Second, for assets exposed to road salt, their serviceability and durability are compromised, which necessitates more frequent inspection and rehabilitation (Li et al., 2013; Suraneni et al, 2016). Finally, underinvested and underserved communities are typically more vulnerable to the environmental and infrastructure impacts posed by the use of road salt, due to lack of resources. As such, there may be social inequality induced by the use of road salt.

2.4.4 Other Considerations

Life of Assets
The service life of motor vehicles and transportation infrastructure under the exposure of road salt can be estimated in terms of their physical life, technological life, economic life, and social and legal life (Ferry and Flanagan, 1991). It is worth noting that the resulting LCC, LCA, and SLCA with a longer-service-life prediction (e.g., over 50 years) is considerably different from a short-term prediction (e.g., less than 10 years). As such, decisions on the service life of these assets should be included in the LCSA framework (Stone, 1980).

Uncertainties and Sensitivity Analysis
Uncertainty is an inevitable factor to consider when implementing the LCSA of road salt (or other WRM products, technologies, or practices). For instance, uncertainties are inherent in the estimation of discount rate in future years, in the dynamics of supply vs. demand of road salt, in deicer usage and frequency (as a function of policy, equipment innovations, climatic conditions, etc.), in corrosion and environmental risks (as a function of the fate and transport of road salt and secondary pollutants), in the safety and mobility benefits achieved from the application of road salt, and so on. In addition, the social impacts of applying road salt can vary greatly by location, cultural, and societal heritage, regulatory practice, technologies, worker environment, etc. In the SLCA, most of the indicators are not easily identified or measured. Furthermore, in light of the limited data available from actual records or statistical analysis, necessary assumptions are often made during the analysis, which adds to the level of uncertainties.

To improve the reliability of the analysis results, it is desirable to conduct sensitivity analysis of LCSA, i.e., by examining how the outcome of LCSA would change by varying each input factor used in the LCSA within a given range or a given statistical distribution.

Information and Feedback
The efficacy of LCSA analysis of road salt largely depends on the information collection and necessary feedback across the entire life cycle of road salt. Currently, there is a significant gap in the data needed to enable a quantitative or semi-quantitative LCSA of road salt. The data on costs (and benefits), environmental impacts, and social impacts need to be collected over a reasonably long duration (e.g., 40 years), from a
diverse yet representative array of scenarios, and in a consistent and ideally standardized format. This is an area where collaborative efforts are much needed between road-way agencies and other stakeholder groups.

2.4.5 The Relationships of LCC, LCA, and SLCA in the LCSA

LCSA is a combination of LCC, LCA, and SLCA with some linear or nonlinear and static or dynamic features. It integrates the impacts of all three pillars of sustainability through the analysis of LCC, LCA, and SLCA, respectively, and provides a reasonable approach to evaluating industrial products or activities from a life-cycle perspective.

Previous research suggested that “The combined impacts, positive and negative, of the sets of measures as a whole, are likely to be more than the simple sum of the impacts of their constituent measures because of synergistic effects” (Lee and Kirkpatrick, 2001). Therefore, the LCSA of road salt has to be considered as a function of LCC, LCA, and SLCA rather than a linear sum of these three branches. Specifically, their mutual effects and interdependencies have become an important factor that determines the assessment results (as shown in Figure 2.4). The expression of their relationships in the original linear equation (2.1) can be rewritten as:

\[ \text{LCSA} = f(\text{LCC}, \text{LCA}, \text{SLCA}) \]  

(2.2)

where each of the functions of LCC, LCA, and SLCA can be expressed as a function of the other two branches, as shown below:

\[ \text{LCC} = f_1(\text{LCA}, \text{SLCA}) \]

\[ \text{LCA} = f_2(\text{LCC}, \text{SLCA}) \]

\[ \text{SLCA} = f_3(\text{LCC}, \text{LCA}) \]  

(2.3)

Figure 2.5 illustrates the interactions between the LCC, LCA, and SLCA of road salt, which must be considered comprehensively in the LCSA process. For instance, vehicle