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Evaluation of Anti-Icing/De-Icing Products Under Controlled Environmental Conditions

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16. Abstract

Snow and ice removal are important tasks during the winter season and large amounts of anti-icing and de-icing chemicals are used and there is a critical need to review and synthesize information from the literature to compare and contrast anti-icing and de-icing chemicals to understand their environmental impact and support decision making. The effectiveness, costs, and environmental impact of commonly used and alternative anti-icing and de-icing chemicals were reviewed in this study. Application of anti-icing and de-icing chemicals may increase ion concentrations in soils and change nitrogen cycle, soil pH, and trace metal concentrations, affect surface water and groundwater, and increase public health risks. Life cycle assessment was conducted to quantitively evaluate environmental impact of selected anti-icing and de-icing chemicals. A decision support tool on environmental impact was developed to evaluate environmental impact of anti-icing and de-icing chemicals in ten different environmental impact categories. The results showed the environmental life cycle assessment tool developed in this study can be used to compare multiple environment impacts to support decision making for winter operation chemicals.

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EXECUTIVE SUMMARY

Introduction

Snow and ice removal are important tasks during the winter season and large amounts of anti-icing and deicing chemicals are used. These anti-icing and deicing products have different physical, chemical, and biological characteristics. With new products being continuously introduced to the market, there is a critical need to review and synthesize information from the literature to compare and contrast anti-icing and deicing chemicals to understand their environmental impact and support decision making. The effectiveness, costs, and environmental impact of commonly used anti-icing and deicing chemicals were reviewed in this study. Life cycle assessment was conducted to quantitively evaluate the environmental impact of selected anti-icing and deicing chemicals. A decision support tool on environmental impact was developed through this study.

Findings

Recent literature on anti-icing and deicing chemicals were reviewed. Phase diagrams can be used to compare eutectic temperatures and concentrations under different temperatures. To achieve similar deicing effectiveness, required concentrations of anti-icing and deicing chemicals will differ. Many factors contribute to the performance of anti-icing and deicing chemicals and corrosion and inhibitors can be added to reduce corrosion and mitigate their impact on long term maintenance costs and infrastructure effects. Alternative products, such as beet juice, glycerol, and glycol can be used as anti-icing and deicing chemicals and show promising results for snow and ice control. Anti-icing can prevent the formation or development of snow and ice on pavement surfaces. Indiana Department of Transportation (INDOT) has expanded the use of anti-icing through the use of brine and other additives in prewetting salt.

The environmental impacts of INDOT's various winter chemicals were reviewed and described herein. Application of anti-icing and deicing chemicals may increase ion concentrations in soils and change nitrogen cycle, soil pH, and trace metal concentrations. Surface water and groundwater may be affected, and public health risks may be increased. Elevated chloride concentration in watersheds could disrupt natural metabolic processes of aquatic organisms. Vegetation may be affected from the high salinity of anti-icing and deicing chemicals. Amphibians are vulnerable to high salinity so salt application near wetlands should be well controlled. Mammals and birds could be affected as well.

Costs of anti-icing and deicing chemicals were compared and service categories and guidance for level of service were reviewed. Traffic condition and weather condition were reviewed, and calculation of bare pavement regain time were discussed.

Direct liquid application can achieve good performance and cost-effectiveness through pre-wetting, treated salt, or slurries. Level of service standards has been produced by INDOT and are used to evaluate performance and effectiveness. This topic is not included in this study.

Additionally, life cycle assessment was used to quantify environmental impacts, such as global warming, acidification, eutrophication, and ecotoxicity, over the entire product's life cycle. Environmental unit processes were established for two conventional deicers (sodium chloride and calcium chloride) and four alternative products (sodium acetate, calcium magnesium acetate, beet juice, and glycerin) to evaluate their environmental impact during winter operations. Chloride-based deicers, like calcium chloride, can impact human health through carcinogenics and noncarcinogenics. Beet juice, glycerin, and calcium magnesium acetate have comparable or higher environmental impacts due to their organic carbon content but have positive environmental impacts on eco-toxicity.

Finally, a decision support tool (DST) was developed to evaluate the environmental impact of INDOT's winter chemicals in ten different environmental impact categories.

Implementation

The environmental impact of ten categories were calculated. The environmental impact of ozone depletion is evaluated based on the emission of chlorofluorocarbons (CFCs) or trichlorofluoromethane that lead to decrease of the stratospheric ozone level. Global warming indicates the average increased temperature in the atmosphere near the Earth's surface and in the troposphere. Photochemical smog formation is an environmental impact included in TRACI. Ozone near the ground is created by multiple chemical reactions between nitrogen oxides (NOx) and volatile organic compounds in the presence of sunlight. Acidification indicates increases concentration of hydrogen ion in the environment that can be attributed to additive acids, additive substances in the water because of acid chemical reactions, biological activities, or natural environment. Eutrophication indicates an aquatic ecosystem with enriched nutrients (e.g., nitrates and phosphates) that can result in accelerated biological productivity, such as algae, weed, and undesirable accumulation of algal biomass. Human health effects of carcinogenics, noncarcinogenics, and ecotoxicity are evaluated. Respiratory effect addresses a subset of criteria pollutants, such as particulate matter and precursors to particles. Resource depletion on fossil fuel is also included. Using a life cycle assessment approach, a case study was developed to analyze three deicing chemicals (1) 23% NaCl, (2) 30% beet juice+70% salt brine, and (3) 30% $CaCl_2$. Results showed the second product had the least ecotoxicity and the third product has greater impacts on human health and ozone depletion. The results showed the environmental life cycle assessment tool developed in this study can be used to compare multiple environment impacts to support decision making for winter operation chemicals.

The DST was used to calculate the environmental impacts from historical chemical usage data and anti-icing and deicing chemicals for all the six districts in Indiana and has been delivered to INDOT for its use. A predictive tool in the DST can help winter operation managers to compare and contrast different anti-icing and deicing chemicals to select the best product for different land use types. The DST tool can be used as a useful tool to help winter operation managers to make informed decisions to improve the selection of products to minimize the environmental impact of snow and ice control.

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1. INTRODUCTION

1.1 Background

Snow and ice removal is the number one priority of Indiana Department of Transportation (INDOT) during the winter season. To improve the traveling public safety, INDOT removes ice and snow from more than 28,000 lane miles of interstates, U.S. highways, and state highways. A significant amount of chemicals and costs are expended on winter operations. For example, a total of 72,794 tons treated salts and 147,745 untreated salts were purchased in six INDOT districts in 2017 at a cost of over $30 million dollars (Indiana Department of Transportation, 2018).

Many different types of anti-icing and deicing products have been used in Indiana. Some commonly used anti-icing and deicing products include rock salt, brine, calcium chloride, magnesium chloride, and beet heet. These products have different physical, chemical, and biological characteristics which have been previously reviewed (Sumsion & Guthrie, 2013). With new products being introduced and studies under controlled environmental conditions being published, there is a need to review and synthesize latest information from literature studies to compare and contrast anti-icing and deicing products. Such a study on the cost-effectiveness and their environmental impact introduces a new analysis parameter to the selection of winter chemicals and improves the environmental consciousness at INDOT for winter operations.

1.2 Scope of Work and Organization of the Report

The objective of this project is to evaluate the effectiveness, costs, and environmental effects of anti-icing and deicing products. A decision support tool (DST) was developed to calculate environmental impacts of winter chemicals.

Chapter 2 describes the results of a literature review on the effectiveness of existing and alternative anti-icing and deicing products, their environmental impacts, and the costs of these products. Chapter 3 presents a level of service analysis. Chapter 4 presents an environmental impact analysis of winter chemicals using life cycle assessment and the decision support tool. Finally, Chapter 5 summarizes the study results.

2. LITERATURE REVIEW

2.1 Effectiveness of Anti-Icing and Deicing Chemicals

2.1.1 Characteristics of Anti-Icing and Deicing Chemicals

The performance of these products under different temperatures can be shown in a phase diagram, such as the example of sodium chloride (NaCl) salt shown in Figure 2.1. The phase diagram is separated by a horizontal line representing the eutectic temperature (-6.02°C or -21.1°F), which is the lowest temperature for the mixture of salt and water to remain liquid. Below the eutectic temperature, the "ice & salt" phase indicates that both ice and salt are in the solid phase and the salt is no longer effective for snow and ice control. Above the eutectic temperature line, there are three phases. The "brine" phase shows that both ice and salt are melted, which is the preferred phase for snow and ice control. When too little salt (<23.3% for NaCl) is applied, the "ice & brine" phase shows that salt is melted but some ice remains in the solid state, which indicates that additional salt is needed for ice to be melted. When too much salt (>23.3%) is applied, the "salt & brine" phase shows that all ice is melted but some salt remains in the solid state, which is fine for snow and ice control but the additional undissolved salt could be saved to minimize costs and reduce environmental

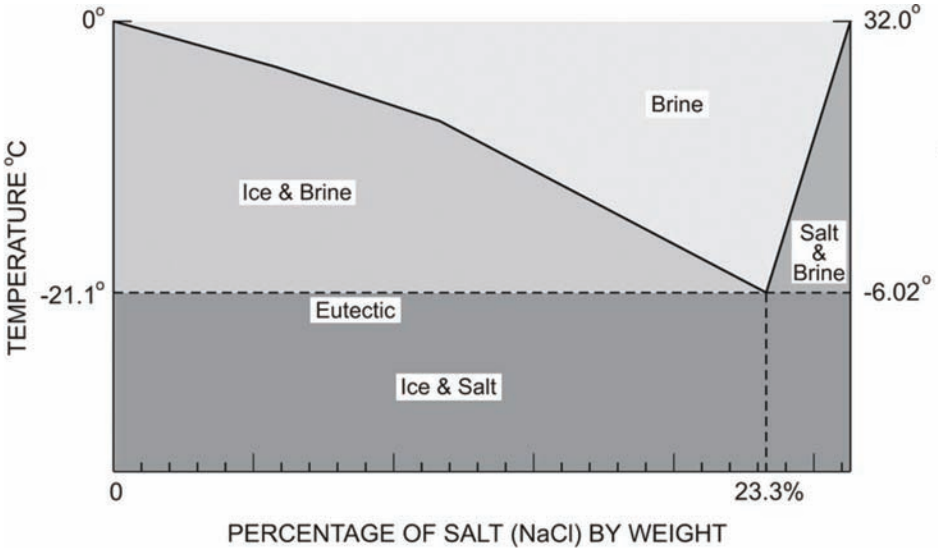

Figure 2.1 Phase diagram for sodium chloride and water (Nixon et al., 2007).

impact. The phase diagram shows that higher concentrations of salts improves the ice melting potential of salt until temperature drops to the eutectic temperature, and further increase of salt concentration results in undissolved salts and does not improve deicing capacity. In reality, concentration of salt may drop significantly when the snow begins to melt, so the actual concentration of salt after snow melting has to be considered.

Commonly used winter chemicals include NaCl, magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), potassium acetate (KAc), and calcium magnesium acetate (CMA). Their eutectic temperatures and concentrations are listed in Table 2.1.

The phase diagrams of commonly used anti-icing and deicing chemicals are shown in Figure 2.2. NaCl, $MgCl_2$, and $CaCl_2$ with similar concentrations have similar performance between 32°F and 25°F, while KAc and CMA with similar concentrations have similar performance between 32°F to -15°F (Ketcham et al., 1996).

To achieve similar deicing effectiveness (freezing point), the required concentrations of the different chemicals differ. For example, KAc or CMA needs higher concentration than that of NaCl to keep solution from re-freezing. To achieve similar freezing point at 15°F, the solution concentration of KAc (18.5%) and CMA (19%) need to be 1.37 times and 1.41 times higher than that of NaCl (13.5%), respectively.

The application rates of different chemicals to achieve similar deicing effectiveness as NaCl at different temperature ranges are shown in Table 2.2. Two examples are provided to illustrate how to use Table 2.2 to calculate application rates.

- *Example 1. Calculate how many gallons of 23% liquid NaCl have similar efficiency as 100 lbs solid NaCl at a temperature between 31°F and 32°F.*

TABLE 2.1
The eutectic temperature and concentration for different chemicals (Ketcham et al., 1996; Olek et al., 2013)

	Eutectic Temperature			Lowest Partial Melting Temperature	
Chemical	**°F**	**°C**	**Eutectic Concentration (%)**	**°F**	**°C**
NaCl	-5.8	-21	23.3	21	-6
$MgCl_2$	-28	-33	21.6	5	-15
$CaCl_2$	-60	-51	29.8	-25	-32
KAc	-76	-60	49.0	-15	-26
CMA	-17.5	-27.5	32.5	20	-6

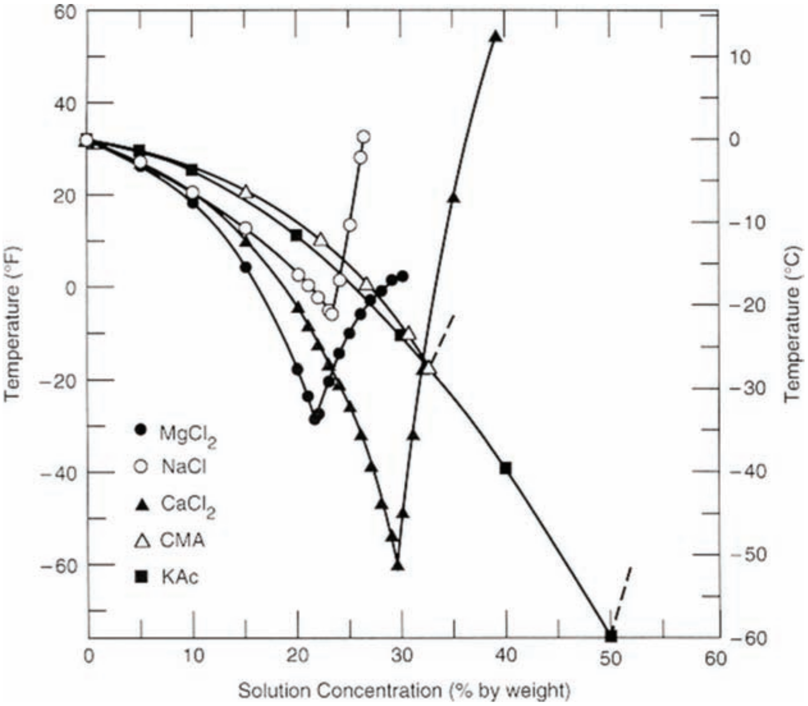

Figure 2.2 Phase diagrams for typical deicing chemicals (Ketcham et al., 1996).

TABLE 2.2
Application rates of different chemicals to achieve similar deicing effectiveness (Amsler, 2014)

	Solid Salt (lbs/lane-mile)					**Liquid Salt (gallon/lane-mile)**				
Temperature Band (°F)	**100% NaCl**	**90%–92% $CaCl_2$**	**100% $MgCl_2$**	**100% KAc**	**100% CMA**	**23% NaCl**	**32% $CaCl_2$**	**27% $MgCl_2$**	**50% KAc**	**25% CMA**
31–32	100	110	90	168	170	44	31	32	32	18
26–30	100	110	90	168	170	44	31	32	32	18
21–25	100	110	93	154	160	44	31	33	29	17
16–20	100	107	88	140	150	44	30	32	26	16
11–15	100	103	85	130	150	44	29	30	24	16
6–10	100	103	83	130	140	44	29	29	24	15
<5	—	—	—	—	—	—	—	—	—	—

TABLE 2.3
Salt application rate guidelines (Nixon et al., 2007)

Prewetted Salt at 12′ Wide Lane	**Category**	**Snow Condition (inch/hour)**	**Salt Application Rate (lbs/lane-mile)**					
			32–30°F	**29–27°F**	**26–24°F**	**23–21°F**	**20–18°F**	**17–15°F**
2 hours plow route	Light	<0.5	50	75	95	120	140	170
	Medium	0.5–1	75	100	120	145	165	200
	Heavy	>1	100	140	182	250	300	350
3 hours plow route	Light	<0.5	75	115	145	180	210	255
	Medium	0.5–1	115	150	180	220	250	300
	Heavy	>1	150	210	275	375	450	525

The following equation can be used to calculate the volume of liquid salt:

$$\mathit{Volume\ of\ liquid\ salt} = \frac{\mathit{weight\ of\ solid\ salt}}{\mathit{mass\ fraction\ of\ solution} \times \mathit{density\ of\ solid\ salt}}$$

To achieve similar efficiency as 100 lbs solid NaCl, the required volume of 23% liquid NaCl is calculated as:

$$\mathit{Volume\ of\ liquid\ NaCl} = \frac{100\ \mathit{lbs\ solid\ NaCl}}{23\% \times 9.79\ \mathit{lbs/gallon}} = 44\ \mathit{gallons}$$

The result indicates that 44 gallons of 23% liquid NaCl has similar efficiency as 100 lbs solid NaCl at a temperature between 31°F and 32°F.

- *Example 2. Calculate how many gallons of 27% liquid $MgCl_2$ have similar efficiency as 100 lbs solid NaCl at a temperature between 16°F and 20°F.*
  If a salt other than NaCl is used, the equivalent weight of salt needs to be identified first. Based on Table 2.2, 88 lbs solid $MgCl_2$ has similar efficiency as 100 lbs NaCl between 16°F and 20°F.
  To achieve similar efficiency as 100 lbs solid NaCl (88 lbs solid $MgCl_2$), the required volume of 27% liquid $MgCl_2$ is:

$$\mathit{Volume\ of\ liquid\ salt} = \frac{88\ \mathit{lbs}\ MgCl_2}{27\% \times 10.35\ \text{lbs/gallon}} = 32\ \text{gallons}$$

The result indicates that 32 gallons of 27% liquid $MgCl_2$ has similar efficiency as 100 lbs solid NaCl at a temperature between 16°F and 20°F.

Although both solid salts and liquid salts are used for snow and ice control, solid salt particles may scatter during spreading and lead to more heterogenous distribution of solid salts than liquid salts. To address this issue, solid salts can be prewetted to minimize the bouncing and scattering problems. Prewetting and direct liquid application could affect the application rate, and therefore it is important to compare the application rate under same pretreatment conditions. The application rate for solid NaCl on a plow route is shown in Table 2.3.

Many factors contribute to the actual performance of anti-icing and deicing chemicals, such as pavement temperature, dusts or other residues that are soluble in water and result in changes of freezing point depression, melting and re-freezing due to friction from passing vehicles, dilution from precipitation, and exposure to sunlight. Therefore, the actual performance of anti-icing and deicing chemicals in the field may vary from their laboratory performance. Field study results of lowest effective working temperatures of chemicals used in Indiana are shown in Figure 2.3, which are different from those obtained in laboratorial studies (Figure 2.1 and Figure 2.2). For example, the theoretical eutectic temperature of $CaCl_2$ is -60°F (Figure 2.2), while the actual field data showed that the lowest freezing point was -53°F (Figure 2.3). Based on Figure 2.3,

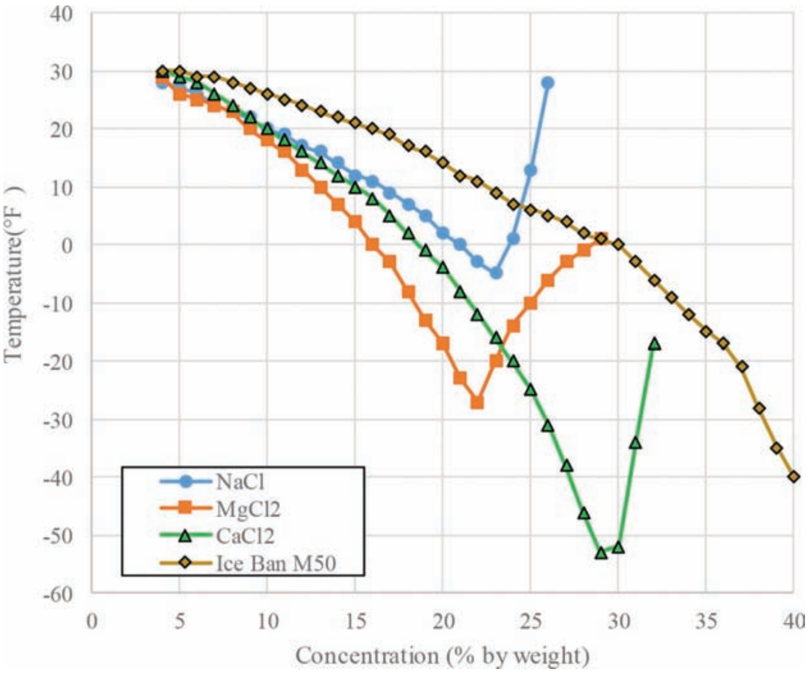

Figure 2.3 Field data of lowest effective working temperatures of different chemicals (Belter et al., 2009).

$MgCl_2$ is preferred when temperature is between -5°F and -27°F as it requires least amount of salts, and $CaCl_2$ is preferred when temperature is below -30°F.

2.1.2 Corrosion Inhibitor

To reduce corrosion and maintenance cost of bridges and pavements, it is a common practice to add corrosion inhibitors to anti-icing and deicing chemicals. A previous laboratory study showed that corrosion was reduced by 70% with the addition of corrosion inhibitors, such as phosphates or carbohydrates (Shi et al., 2011). Calcium nitrite or nitrate could postpone the initiation of reinforcement corrosion and their preferred concentrations were proposed in Table 2.4 (Al-Amoudi et al., 2003). However, the actual time for nitrite to penetrate concrete must be considered when corrosion inhibitors are applied.

Although concentrations of anti-icing and deicing chemicals are expected to be correlated with their effectiveness for snow and ice control, a previous study of one solid NaCl deicer (IceSlicer Elite) and three liquid corrosion inhibitor-containing deicers (NaCl deicer (NaCl+GLT), $CaCl_2$ deicer (CCB), $MgCl_2$ deicer (Freez-Gard CI Plus)) showed that effectiveness of corrosion inhibitors was not related with their concentrations (Shi et al., 2011). Their results showed the lowest percent corrosion rate (PCR) value was observed with relative low inhibitor concentration (3.4%) in NaCl+GLT (Shi et al., 2011).

The performance of four corrosion inhibitors (calcium nitrate corrosion inhibitor, calcium nitrite-based corrosion inhibitor, migratory corrosion inhibitor corrosion inhibitor and organic corrosion inhibitor) was compared in a previous study (Al-Mehthel et al., 2009). Corrosion density was measured as an indicator of corrosion according to ASTM C 876 and the results showed that corrosion inhibitors could increase the time of reinforcement initiation of corrosion and cracking of concrete specimens. As shown in Table 2.5, organic corrosion inhibitor had the best performance followed by migratory corrosion inhibitor.

TABLE 2.4
Preferred corrosion inhibitors for different contamination (Al-Amoudi et al., 2003)

Contamination	Preferred Corrosion Inhibitors
Chloride	4% calcium nitrite or 4% calcium nitrate
Chloride and sulfate	4% calcium nitrite or 3% calcium nitrate
Sea water	4% calcium nitrite
Brackish water	2% calcium nitrite
Unwashed aggregate	4% calcium nitrate

The application frequency of corrosion inhibitors may be lower than those of anti-icing or deicing chemicals, as a large amount of corrosion inhibitors can remain on the highway. For example, up to 80% of corrosion inhibitor remained on the pavement after four days application of $CaCl_2$ (Shi et al., 2011).

2.1.3 Alternative Products

In addition to conventional anti-icing and deicing chemicals, alternative products have been used for snow and ice control. Several representative alternative products are reviewed in this section.

TABLE 2.5
Time to initiation of reinforcement corrosion and cracking of concrete (Al-Mehthel et al., 2009)

		Time to Initiation of Reinforcement Corrosion, Days			Time to Cracking of Concrete Due to Accelerated Corrosion, Hours		
Corrosion Inhibitor	**Applied Process**	**0.4% Cl^-**	**1% Cl^-**	**2% Cl^-**	**0.4% Cl^-**	**1% Cl^-**	**2% Cl^-**
None	N/A	480	320	Active	77	55	36
Calcium nitrate	N/A	520	510	Active	83	62	52
Calcium nitrite-based[1]	During mixing	530	370	Active	85	61	43
Migratory[1]	Surface of concrete	No corrosion	No corrosion	Active	201	153	64
Organic[1]	During mixing	No corrosion	No corrosion	370	487	246	89

[1] Proprietary corrosion inhibitor.

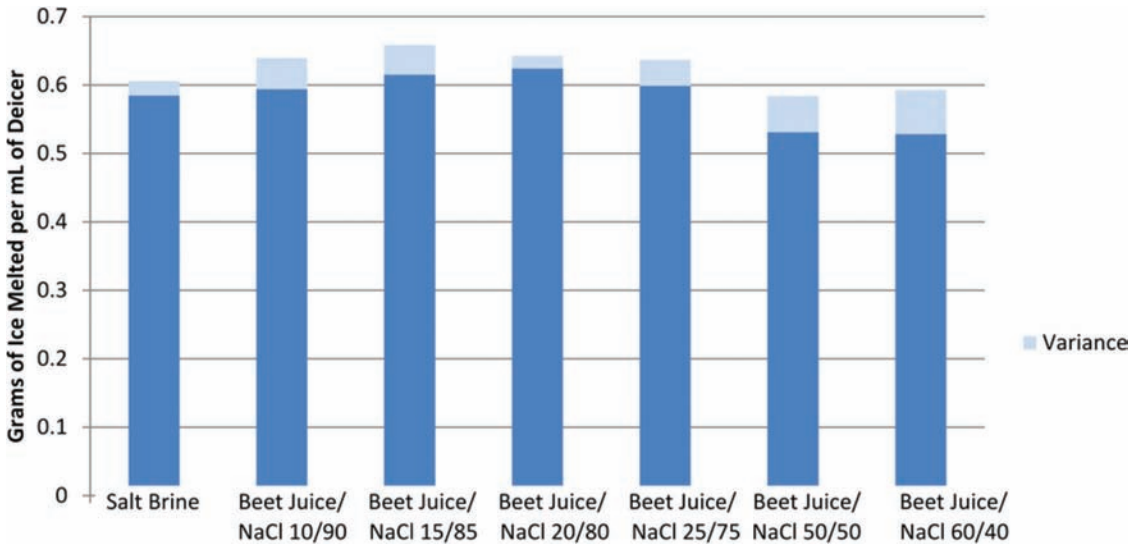

Figure 2.4 Shaker test results for beet juice mixes at 20°F (Gerbino-Bevins, 2011).

2.1.3.1 Beet juice. Beet juice is an alternative organic chemical with a lower freezing point than water and has been used as a prewetting and anti-icing chemical and a performance enhancer but has not been used as a deicing chemical. The color of beet juice is almost black and therefore its performance increases sharply under exposure to sunlight. However, significant enhancement has not been observed using beet juice as a prewetting and anti-icing agent (Fu et al., 2012). As a melting enhancer, beet juice needs to be mixed with chloride, acetate, or other deicing chemicals. Beet juice could help NaCl stick to ice more efficiently to enhance ice melting capacity and minimize application rate. Two kinds of beet juice were blended with NaCl, the maximum melt capacity occurs at 15% beet juice and 85% NaCl. It performs better than NaCl alone (Gerbino-Bevins, 2011). In addition, high mixture composition of beet juice (e.g., 50% beet juice and 50% NaCl) or low concentration of beet juice (e.g., 10% beet juice and 90% NaCl) does not have higher melting capacity than that of 15% beet juice and 85% NaCl (Figure 2.4), because high stickiness capacity from beet juice helps the sodium chloride stick to ice cannot compensate melting capacity from NaCl (Gerbino-Bevins, 2011).

Field tests were conducted using beet juice in prewetting application or direct liquid application (Fu et al., 2012). Comparison between salt brine and mixture of beet juice and salt brine as prewetting or anti-icing agents was conducted at a multilane arterial street, whose annual average daily traffic volume ranges from 16,000 to 18,000 (Fu et al., 2012). The composition, application rate, and costs are shown in Table 2.6 and Table 2.7.

The performance differences among salt brine and two organic mixtures in prewetting application for one particular day were mostly small and organic mixture showed slightly better performance than salt brine (Figure 2.5).

Additional testing showed that organic materials showed better performance than brine and the difference in friction up to 30% (Figure 2.6). However, the observed differences could be attributed to different traffic conditions or other local phenomena (Fu et al., 2012).

TABLE 2.6
Prewetting application rate for salt brine and organic mixture (Fu et al., 2012)

Chemical	Composition	Total Material Per Lane (kg/km)	Dry Salt Per Lane (kg/km)	Liquid Per Lane (kg(L)/km)	Cost Per Lane ($/km)
Salt brine	23% NaCl + water	60	48	12 (10)	3.6
		85	68	17 (14.2)	5.1
		110	88	22 (18.5)	6.6
Organic mixture	30% beet juice + 70% salt brine (M1 and M2)	60	57	3 (2.5)	4.02
		85	80.57	4.25 (3.5)	5.6
		110	104.5	5.5 (4.5)	7.37

TABLE 2.7
Direct liquid application rate for salt brine and organic mixture (Fu et al., 2012)

Chemical	Composition	Total Material Per Lane (kg/km)	Total Salt (NaCl) Per Lane (kg(L)/km)	Cost Per Lane ($/km)
Salt brine	23% NaCl + water	100	23	1.2
Organic mixture	30% beet juice +70% salt brine (M1 and M2)	85	17 (14.2)	5.1

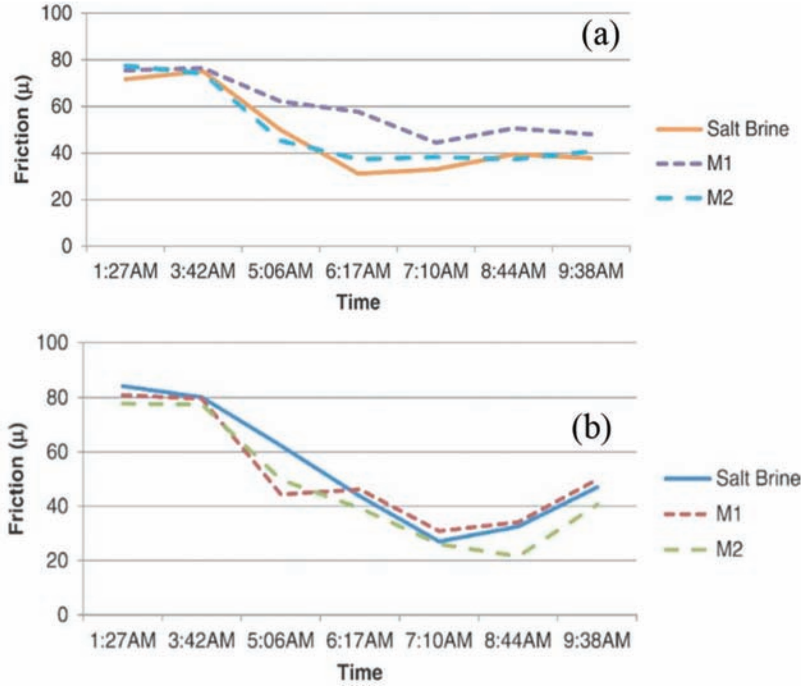

Figure 2.5 Average friction for anti-icing chemicals with (a) direct liquid application and (b) prewet salt (Fu et al., 2012).

2.1.3.2 Mixture of conventional chemicals. Deicing chemicals could be mixed to enhance their melting capacity and bare pavement regain time (BPRT). A few existing mixtures of alternative products, components, and costs are summarized in Table 2.8. A comparison study conducted with 300 tests in 21 real-world snow events showed that the average BPRT of Blue salt, green salt, Jet blue, and slicer decreased 0.4, 0.7, 1.05, and 1.25 hours than that of rock salt, respectively (Hossain et al., 2015). Jet blue had a considerable reduction of 3.75 hours in BPRT at -8°F. Slicer worked well in both plowed and unplowed section, while Jet Blue could be a choice only in a plowed section. In addition, these alternative products had better performance with lower application rates than rock salt when pavement temperature was below 23°F (-5°C) (Hossain et al., 2015). The results showed that that alternative products could reduce the application rate significantly at extreme low temperatures, although their costs are higher than that of rock salt.

The melting capacity of different chemical mixtures was tested using the Strategic Highway Research

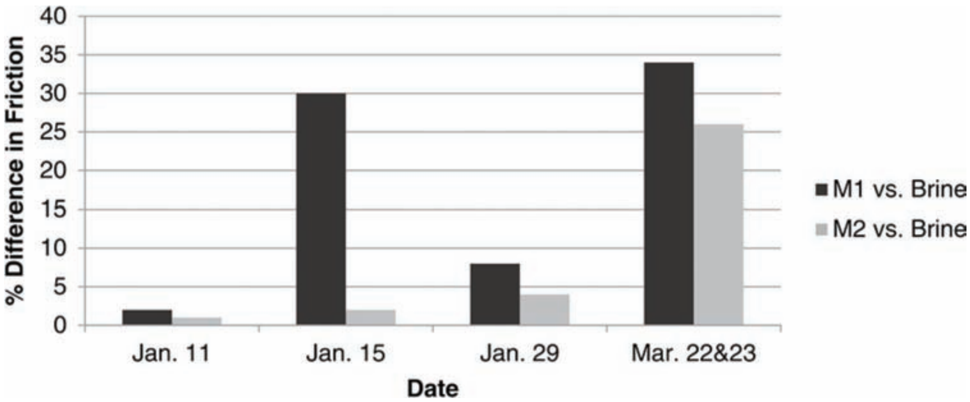

Figure 2.6 Average percentage of difference in friction in direct liquid application (Fu et al., 2012).

TABLE 2.8
List of alternative products, components, and prices (Hossain et al., 2015)

Products	Composition	Cost ($/ton)
Rock salt	NaCl	80
Blue salt	NaCl treated with $MgCl_2$	100
Slicer	78% NaCl, 9.4% $MgCl_2$, and 2–3% propriety ingredient	358
Green salt	NaFm treated with GEN3 runway deicing fluid	950
Jet blue	NaCl treated with proprietary polyol	495

TABLE 2.9
Ice melting test of deicing chemicals at different temperatures

	Average Volume (mL) of Collected Brine After 60 Mins					Test Method	Reference
Deicing Chemicals	**30°F**	**20°F**	**15°F**	**10°F**	**0°F**	**—**	**—**
23% NaCl	3.5	—	1.1	—	—	M-SHRP	(Akin & Shi, 2010)
32% $CaCl_2$	4.0	—	1.6	—	—	M-SHRP	(Akin & Shi, 2010)
30% $MgCl_2$	4.3	—	1.6	—	—	M-SHRP	(Akin & Shi, 2010)
95% NaCl + 5% $CaCl_2$	3.8	—	1.0	—	—	M-SHRP	(Akin & Shi, 2010)
90% NaCl + 10% $CaCl_2$	4.0	—	1.2	—	—	M-SHRP	(Akin & Shi, 2010)
85% NaCl + 15% $CaCl_2$	3.8	—	1.1	—	—	M-SHRP	(Akin & Shi, 2010)
80% NaCl + 20% $CaCl_2$	4.0	—	1.1	—	—	M-SHRP	(Akin & Shi, 2010)
NaCl (solid)	—	—	—	—	0.6	M-SHRP	(Akin & Shi, 2010)
$CaCl_2$ (solid)	—	—	—	—	2.1	M-SHRP	(Akin & Shi, 2010)
$MgCl_2$ (solid)	—	—	—	—	1.7	M-SHRP	(Akin & Shi, 2010)
NaCl	9.0	2.4	—	1	1.4	SHRP	(Nixon et al., 2007)
CMA	—	3.9	—	1.8	0.8	SHRP	(Nixon et al., 2007)
KAc	7.0	2.0	—	—	—	SHRP	(Nixon et al., 2007)
Beet juice	—	3.3	—	—	—	SHRP	(Gerbino-Bevins, 2011)

Program (SHRP) method and the results are summarized in Table 2.9. The application rate based on modified SHRP (M-SHRP) was higher than typical field application rates. But the test was conducted in parking lots and did not include effects of traffic condition, mixing, and ultraviolet radiation. Therefore, further studies of their effectiveness and cost under the influence of real traffic conditions are needed.

Additionally, agriculturally derived products and complex chloride mineral (CCM) based products are increasingly used in snow and ice control operations. These products can be either applied alone or combined with traditional chloride-based chemicals. Some commercially available agro-based liquid deicers include GEOMELT, Magic Minus Zero, Magic Salt, Icenator, Bare Ground, Caliber M1000, IceBan, and Ice Bite. Some novel liquid deicing chemicals contain complex chlorides and mineral products and also attract attention as they are produced from natural resources. For instance, Aqua Salina with component of 10%–11% $CaCl_2$, 7%–8% NaCl, 2%–3% $MgCl_2$, and 1% KCl could significantly enhance ice or snow melting performance of rock salt.

2.1.3.3 Glycerol and glycol. Glycerol ($C_3H_8O_3$) is a widely used agriculture deicing chemical because of its cost-effectiveness and low corrosiveness. Glycerol is usually obtained as a by-product of soap manufacturing processes, biodiesel production processes, and other industrial processes of trans-esterification, hydrolysis, or saponification. For commercial biodiesel production, approximately 0.35 kg of crude glycerol could be produced from each gallon of biodiesel with an attractive price of \$0.02 per gallon (Pachauri & He, 2006). Adding glycerol to NaCl salt can increase anti-icing performance at cold temperature through reduced application rates, and less corrosion to metal, concrete, or asphalt material on pavement. Previous studies indicated that the viscosity of a mixture of 20% NaCl and 80% glycerol was suitable for distribution and its freezing temperature, eutectic temperature, volume of ice melting, and percentage of skid resistance were superior than other combinations of NaCl or $MgCl_2$ with Geomelt (renewable sugar beet), Ice B Gone (molasses, high-fructose corn syrup, or other carbohydrate base), BioOil (liquid fuel derived from agriculture or forest residual), or E310 (powder alkaline-washed corn hull) (Taylor et al., 2010).

In addition to glycerol, glycol ($C_2H_6O_2$) is also an efficient freezing point depressant and considered as a deicing product at extremely low temperatures. Ethylene glycol ($(C_2H_4O)_nH_2O$) can lower the freezing point of water to -50°C. Propylene glycol ($C_3H_8O_2$) is a slightly viscous liquid and its freezing point is -13°C (Ritter, 2001).

A summary of glycol and glycerol is listed in Table 2.10.

2.1.4 Comparison of Different Anti-Icing and Deicing Chemicals

Based on the information collected from the Clear Road Technical Advisory Committee, the Pacific Northwest Snowfighters Association, the Aurora Program, the Winter Maintenance Technical Service Program, and 1st National Winter Maintenance Peer, the following aspects have been identified as key performance indicators to assess anti-icing and deicing chemicals for winter maintenance (Akin & Shi, 2010):

- effective temperature range,
- melting ability or capacity,
- eutectic temperature (and concentration),
- residual characteristics,
- ability to prevent bonding between ice/snow and the pavement,
- deicer bounce (the characteristic of not adhering or settling on an inclined surface),
- ability to undercut or break the bond between ice/snow and the pavement,
- penetration ability on ice, and
- penetration ability on compacted snow.

To evaluate ice melting capacity of deicing chemicals, Shaker Test can be done in a modified martini shaker to simulate the effect of traffic on the roadway. Shaker Test has several advantages over the SHRP Ice Melting Capacity Test, i.e., the results of Shaker Test are not affected by the size of freezer, can be repeated between laboratories, and can avoid errors induced by mixing liquid deicer in SHRP Ice Melting Capacity Test (Gerbino-Bevins, 2011). The results of Shaker Test for the effectiveness of various chemicals under different temperatures is shown in Table 2.11.

2.1.5 Anti-Icing Process

There are two distinct strategies to apply freezing-point chemicals: anti-icing and deicing. Anti-icing process aims at preventing the formation or development of bonding snow and ice for easy removal, while deicing processes aims at breaking the existing bond in snow or ice (Ketcham et al., 1996). Deicing operation is typically initiated after snow has accumulated one inch (25 mm) or more. A typical anti-icing process is summarized in Figure 2.7.

Abrasive treatment provides additive friction for anti-icing during operations and they can enhance surface friction when snow or ice is bonded to surface strongly and not easily removed. Although abrasives are considered as short-term treatment due to its easy dispersion by traffic, no obvious disadvantages have

TABLE 2.10
Summary information on glycerol and glycol (Fay et al., 2015)

Characteristics	Glycerol	Glycol
Temperature ranges	Low freezing point if mixed with water.	Low freezing point if mixed with water. Propylene glycol could be effective to -74°F.
Application rate	N/A	50–2,000 gal/lane (at 55% or 45% glycol concentration)
Cost	\$10–\$30/gal	\$14–\$40/gal for ethylene glycol and \$10–\$20/gal for propylene glycol.
Performance	Often used as an anti-freezing or ice-inhibiting constituent and can be used as exterior coating to avoid caking in storage.	Often used to deice aircrafts.
Storage	As solid: Loading should be applied inside building or on non-permeable pad. Spilled material should be cleaned up as soon as possible. As liquid: Ideally in double walled tank on a non-permeable pad. Storage tanks need secondary containment to retain at least 110% volume of the largest tank. Spilled material should clean up as soon as possible.	

TABLE 2.11
Effectiveness comparison based on Shark test for deicer treatment (Gerbino-Bevins, 2011)

Treatment	Main Chemical	By-Product	Weight of Ice Melted (g of ice melted/mL deicer or g deicer)		
			20°F	10°F	0°F
Liquid treatment	29% $MgCl_2$	—	1.065	0.91	0.667
	30% $CaCl_2$	Beet juice	1.051	0.898	0.704
	49% KAc	—	1.405	0.868	0.656
	30% $MgCl_2$	—	1.062	0.781	0.533
	26.9% $MgCl_2$	Carbohydrate	0.978	0.736	0.577
	25% $MgCl_2$	Carbohydrate	0.969	0.675	0.546
	15/85 mix of beet juice/NaCl	23% NaCl	0.636	0.326	0.0
	23% NaCl	—	0.595	0.302	0.0
Solid treatment	NaCl	—	1.05	0.61	N/A

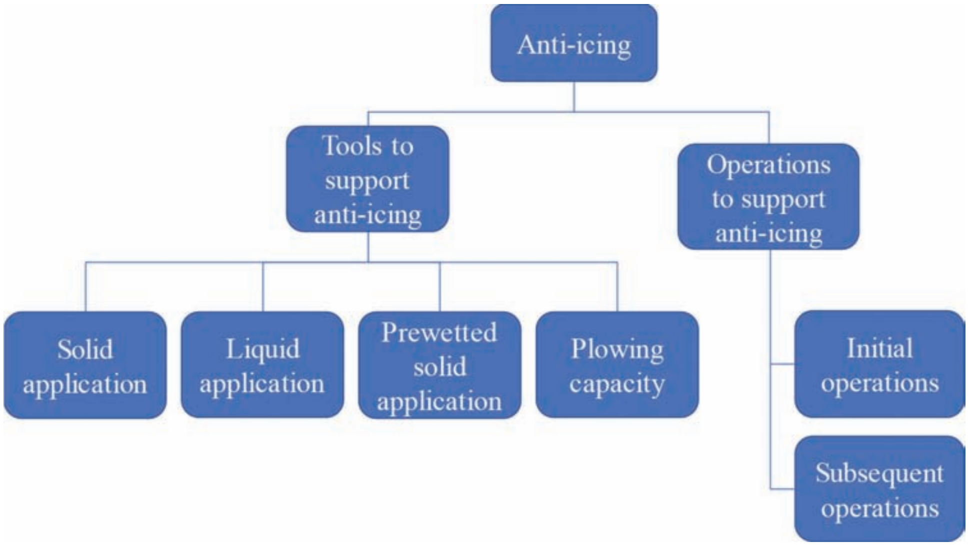

Figure 2.7 The anti-icing process (Ketcham et al., 1996).

been observed with abrasive treatment (Ketcham et al., 1996).

Dry solid chemicals are more effective if the surrounding environment provides sufficient moisture. For initial operations, the application timing is important. Solid chemicals are effective if maintenance operators disperse chemicals right after enough accumulation of precipitation and before the development of bond between precipitation and road (Ketcham et al., 1996). For subsequent operations, solid chemicals are effective if adequate moisture after storms is accumulated. However, chemicals may be lost due to high speed and commercial vehicles or bouncing particles during spreading. Solid spreaders, such as hopper type spreaders or dump body spreaders, are used to minimize bouncing particles. The typical rebound distance is no more than 0.5 m from pavement with a conventional spreader spinner (Ketcham et al., 1996).

Direct liquid application is a process that applies chemical liquids onto a road surface. Direct liquid application can be used as pretreatment to prevent the formation of bond between snow and road surface and to make the plowing process easier. Direct liquid application is effective as liquids provide faster reaction rate compared with granular salts and direct liquid application can avert bond of snow or ice (Ketcham et al., 1996). Direct liquid application at -5°C (23°F) or above achieves its best performance, while direct liquid application below -5°C leads to increased application rate and diminished cost efficiency. However, applying chemicals before sufficient precipitation may resulted in chemical dilution. Because of the limitations of liquids, chemicals may need to be reapplied more than once. The typical direct liquid application equipment for highway operation are Nozzle-type spreader and Spinner-type spreader.

2.1.6 Prewetting

Prewetting is a process to spray or coat solution salts or other liquid chemicals before applying salts on the ground. Prewetting is usually considered to be effective for two reasons. First, prewetting improves adhesion to the pavement and minimizes scatter problems with applied chemicals. Second, prewetting could draw moisture and activate salts if solid chemical particles are covered with liquid film. If solid deicers are immediately spread after the prewetting process, the moisture could facilitate activation for a longer time period.

Fine size particles are appropriate for prewetting solid chemicals for anti-icing. Although large particles with greater weight could move faster and easily penetrate precipitation to the pavement, such an advantage is less obvious for anti-icing activities with minimal amount accumulation of snow or ice. In addition, fine particles are dissolved to solution faster due to large relative surface area and cover pavement surface faster.

$CaCl_2$ with a low freezing-point serves as a common prewetting chemical. It can absorb moisture from air with a relative humidity of 42% or higher. Based on field tests, saturated $CaCl_2$ solution (20%) applied to salts at the rate of 30% by weight is effective. Other prewetting solutions include $MgCl_2$, KAc, and CMA, which have lower freezing-points than that of NaCl. Water is a practical prewetting solution used at high temperatures above 32°F.

Prewetting can be achieved through three approaches:

1. Prewetting of stockpile—liquid chemical is injected into stockpile at a specified dosage. Prewetting of stockpile should be done when the temperature of stockpile drops to 0°C (32°F) in the late fall. The advantages of this method include that no spray equipment is needed to be purchased and maintained, no storage tank is needed, and no further training for application operators are needed. Some highway agencies have abandoned this approach because rain or snow coated on the wetted stockpile may dilute chemicals and mitigate the pile. Therefore, it is important to place stockpile on impervious asphalt or concrete floor or cover the stockpile.
2. Prewetting of a load or while loading—spraying liquid chemicals with a loaded spreader, such as an overhead sprayer with nozzles. The disadvantages of this method that corrosion on truck equipment is high, the unused portion of truck containing loaded materials cannot be discharged, and uniform distribution of particle coating cannot be guaranteed.
3. Prewetting by spreader spray system—spreader could apply liquids directly to the material being spread via on-board spreader spray system. Highway agencies face frequent failures of electric pumps and spray nozzle clogging and this equipment typically experiences operational problems.

2.2 Environmental Impacts

2.2.1 Soil

Anti-icing and deicing chemicals may affect both chemical (ion concentrations or trace metals) and physical (structure) characteristics of soils. Without the impact of human activities, the majority of cations in soils come from the weathering process of parent rocks, while some cations come from ocean, geologic deposits, saline groundwater, and volcanic activity (Mullaney et al., 2009). The concentration on exchange of cations generally reflects their concentration in parent rocks, but concentration on exchange are also related with their charge and size. Aluminum (Al) has the highest concentration in parent rocks and highest positive change (+3) among all cations in rocks and has the highest cation exchange capacity. Concentrations in parent rocks and soils due to cation exchange of common cations are listed in Table 2.12. Calcium (Ca) and potassium (K) have similar concentrations in rocks. As Ca has two positive charge (+2) and K has one positive charge (+1), therefore both Ca and K have less cation exchange capacity than that of Al. Although K has the second highest concentration in parent rock, its single charge makes it ranked fourth in all cations. Sodium (Na) has the low concentration in most rocks and its charge is one (+1), and therefore Na has the least cation exchange capacity compared with other cations (Kelting & Laxon, 2010).

The application of anti-icing and deicing chemicals increases concentrations of ions in top soils, but ion concentrations decrease with the increasing depth of soils. A previous study showed that deicing salt concentration on upper soil layer (0–15 cm) rose significantly from 0.05 mg/g dry soil to 5.04 mg/g dry soil after 27 days of application of 0.25 L 200 g/L deicing salt solution (Ke et al., 2013). The cation exchange could influence ion concentrations in soils. Soils containing clays and organic matters have surfaces that are negatively charged and can neutralize positive charge of cations in the soil. A chemical bond can form between negative charge and positive charge through a weak electrostatic attraction and makes it possible to transform cations from soil surface to soil solution or vice versa, which is known as cation exchange (Jenks et al., 2007). Cation exchange capacity (CEC) illustrates the ability for cation to replace another cation on soil's surface that has weaker affinity to soil or smaller concentration. At the same concentration, the relative adsorption affinity ranking from high to low is listed as follows: $H^+ > Al^{3+} > Ca^{2+} > Mg^{2+} > K^+ > Na^+$. In addition to ions introduced from deicers, nitrogen cycle and heavy metals may be affected by deicers as well. A field-study confirmed that episodic introduction of road salt severely disrupts soil nitrogen recycle at a range of spatial and temporal scales (Green & Cresser, 2008). Ammonium and nitrite are major nitrogen compounds absorbed by a large number of plants. Ammonium-N (NH_4^+-N) is a cation and its retention on cation exchange sites is reduced by cations introduced from road salts.

Application of road salts also causes pH value to increase in natural acidic land and reduce mineralizable-N pool of sideroad soil. In the area that was directed affected by salts, the ammonium proportion of CEC declined from 0.62% in 2 m away from the edge of road to 0.11% in 16 m away from the wall, and thereafter increased 0.18% as distance from highway was 64 m (Figure 2.8) (Green & Cresser, 2008).

Deicing chemicals also increase trace metal concentrations of roadside soils due to metal mobilization

TABLE 2.12
Cation concentration in parent rocks and cation exchange for soils not adjacent to road (Kelting & Laxon, 2010)

Cation	Concentration in Parent Rock (mg/kg)	Concentration in Soil Because of Cation Exchange (mg/kg)
Al^{3+}	47,369	1,085
Ca^{2+}	11,684	584
Mg^{2+}	3,118	45
K^{+}	19,272	31
Na^{+}	2,649	5

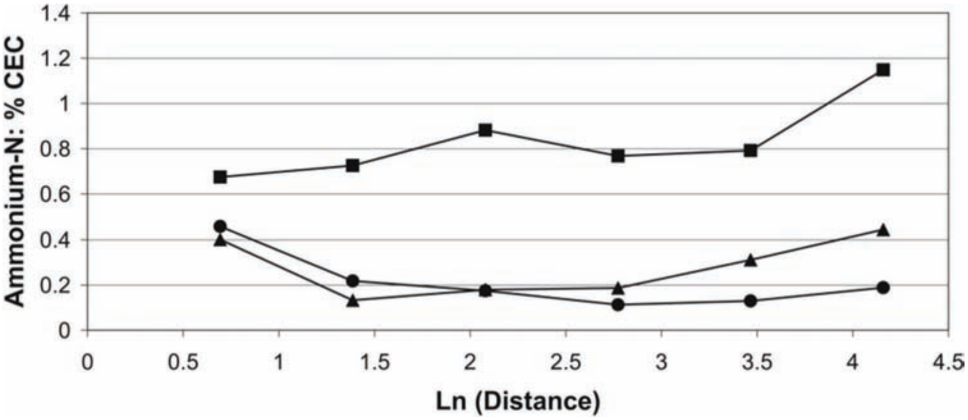

Figure 2.8 Mean percentage ammonium-N occupation of CEC for 2, 4, 8, 16, 32, and 64 m from a road's wall (Green & Cresser, 2008).

resulted from cation exchange, chloride complex formation, and colloid dispersion. Heavy metals in roadside may originate from different sources (Table 2.13) and are widely detected in roadside soils (Table 2.14). Although the concentrations of trace metals in soils are relatively low, their toxicity to vegetation, animals, and human exceeds other metals.

Previous studies showed that sodium salts had higher release effect on cadmium (Cd) and less release effect on lead (Pb) and copper (Cu), when compared with magnesium (Mg) salt (Nelson et al., 2009). After NaCl treatment, high concentrations of Cd and Pb were detected in roadside soils. A high correlation between the mobilization of Cd and Cl was observed (Li et al., 2015). Cation competition and formation of heavy metal complexes increase solubility of heavy metals in water and these trace metals can be released from soils to reach ground water or surface water.

Additionally, deicing chemicals may affect soil structure, which is the arrangement of solid particles, such as size and shapes of soil aggregates and pore space among these particles, clusters of mineral, and organic material. Well-structured soils have high infiltration rate with surface runoff on the soil and high stability to resist degradation and potential erosion. Bivalent Ca^{2+} and Mg^{2+} cations improve soil structure through cationic bridging between clay particles and soil organic carbon (Figure 2.9), and therefore Ca^{2+} and Mg^{2+} cations are important to maintain soil structure under arid and semi-arid conditions, where calcium carbonate and magnesium carbonate precipitates form secondary carbonate coating and bond primary soil particles together (Bronick & Lal, 2005).

TABLE 2.13
Heavy metals commonly found in roadside and their sources (Public Sector Consultants Inc., 1993)

Heavy Metal	Traffic Source
Cadmium	Diesel oil, tire wear
Chromium	Metal planting, brake lining wear
Copper	Metal plating, brake lining, bearing wear
Iron	Vehicle rust, highway structures, engine parts
Lead	Tire wear, lubricating oils, and grease, bearing wear
Zinc	Tire wear, motor, grease

Although Na^{+} adsorption affinity is lower than that of Ca^{2+} and Mg^{2+}, high concentration of Na in deicing chemicals may displace Ca^{2+} and Mg^{2+} and plays a role to hold clays together, which is consistent with the negative correlation between Na/CEC and Ca/CEC. However, Na scatters existing aggregation and disperses clays and increases surface runoff. Then individual particles (colloids) begin to suspend in the soil solution and transport to groundwater or surface water. During this process, suspended particles may also bond trace metals to release trace metals from soils and reach groundwater or surface water. A positive correlation was observed between the degree of colloid dispersion and lead (Pb) concentration (Norrström & Bergstedt, 2001).

TABLE 2.14
Mean concentrations of heavy metals (mg/kg) detected in roadside soils

Location	Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Nickel (Ni)	Lead (Pb)	Zinc (Zn)	Reference
U.S. Great Plains	1.46	147	94.1	129	129	321	(Elrashidi et al., 2016)
Vermont, U.S.	0.75	0.15	0.75	0.5	2.2	6.9	(Grubinger & Ross, 2011)
U.S. EPA Level requiring clean-up	70	230	—	1,600	400	23,600	(U.S. Environmental Protection Agency, 2002)

Figure 2.9 Cation bridging due to calcium involvement and aggregation of clays (Kelting & Laxon, 2010).

TABLE 2.15
The ratio of base cation and CEC of roadside soils at different depths and distances from road (Norrström & Bergstedt, 2001)

Distance (m)	Depth (m)	Ca/CEC (%)	Mg/CEC (%)	K/CEC (%)	Na/CEC (%)	pH
0.2	0–5	66	4.0	2.8	27	7.4
	5–10	58	6.5	3.1	32	7.1
	10–15	60	7.5	2.7	30	7.0
2	0–5	60	9.5	4.4	26	7.0
	5–10	57	14	3.7	25	6.9
	10–15	55	8.6	3.3	33	6.5
6	0–5	60	21	2.2	17	6.4
	5–10	58	22	2.5	17	6.7
	10–15	58	24	2.4	16	7.0
10	0–5	75	19	1.8	3.6	6.4
	5–10	77	18	1.8	3.3	6.4
	10–15	77	18	2.0	2.2	6.4

The effects of deicing chemicals on soils may be affected by other factors. The filtration rate of soil depends on soil structure that affect melting of snow and ice carrying chemicals or run off through surface. Drainage system transport runoff to surface water or groundwater. Traffic flow determines trace metals' concentrations in soils. Road conditions determine the length that runoff streams away from sideroad. Significant impact identified within 6 m from road is shown in Table 2.15 (Norrström & Jacks, 1998), and measurable impact can be observed up to 30 m. In a comparative study between high road salt input versus low road salt input, significantly enhanced cation exchange of Na for high salt input was compared with low salt input out to 14 m (Kelting & Laxon, 2010). Assuming an average distance of 6 m for measurable impacts of road salt on soils, about 12 square meter per lane meter or 24 square meter per centerline meter were affected by road salts.

Acetate salts are considered as biodegradable. Acetate ions are the most abundant organic acid metabolite in nature. Because of its half-life is less than two days under 7°C (45°F), acetate salts could be easily degraded by soil microorganisms. CMA could theoretically influence the mobility of metals in soils, because acetate could encircle and bond Mg or Ca, which is known as chelating effect. However, degradation of acetate happens so rapidly that little acetate transforms to chelate and stays in soils.

2.2.2 Surface Water and Groundwater

Surface water quality criteria for chloride in Indiana has been established as a function of hardness (in mg/L as $CaCO_3$) and sulfate (in mg/L). Chloride criteria may only be established on sulfate concentration when it is greater than the water quality criterion for sulfate and details are listed in subdivision 327 IAC 2-1.3 in Water Quality Standard of Indiana (Indiana Department of Environmental Management, 2013). The following equations provide chloride acute aquatic criterion (AAC) and chronic aquatic criterion (CAC) as a function of hardness and sulfate:

$$\text{AAC} = 287.8\ (\text{hardness})^{0.205797}\ (\text{sulfate})^{-0.07452}$$
$$\text{CAC} = 177.87\ (\text{hardness})^{0.205797}\ (\text{sulfate})^{-0.07452}$$

Groundwater or surface water could be affected near salted roads. The parameter salinization indicates the concentration of total dissolved solid in water could increase when concentration of chloride and mobilizable anion of various salts increase (Kaushal et al., 2005). In U.S. surface waters, chloride concentrations usually range from 0 to 100 mg/L and most concentrations were lower than 20 mg/L (Wetzel, 2001). The average concentration for rivers in North America is around 8.0 mg/L (Wetzel, 2001). An Adirondack Lakes Assessment Program (ALAP) analysis of chloride concentration in 114 lakes with majority of them locating near the salted roads showed an average chloride concentration of 8.8 mg/L, which was 22 times higher than the average chloride concentration at another survey by Adirondack Lakes Survey Corporation (ALAS), in which most lakes were far from salted roads. Furthermore, 20% of ALAP lakes chloride concentration exceeded 11 mg/L. The differences in chloride concentrations showed that deicing chemicals had increased chloride concentrations in lakes. Chloride criteria recommendation from EPA for fish species showed that chloride concentration should not exceed a 4-day average of 230 mg/L and acute concentration should not exceed 1-hour average of 860 mg/L, and both of them should not exceed more than once every 3 years on (U.S. Environmental Protection Agency, n.d.). A previous study estimated that 5% of aquatic species in the stream were affected if chloride concentration is over 210 mg/L and 10% of them could be affected if the concentration is over 240 mg/L (Canadian Environmental Protection Act, 2001).

One identified public health risk related to deicing chemicals on water supplies is toxemia during pregnancy, but most regulations for water supply systems did not identify high chloride concentration something to alert the public about on the basis of Figure 2.10 (Mullaney et al., 2009). The samples were collected from 1,332 sites from 1991 to 2004, and chloride concentrations in a small proportion of total samples (less than 1.5%) exceeded the criteria and majority chloride concentration (99.8%) were less than 860 mg/L (Mullaney et al., 2009).

Sample collection from surface water for chloride measurements is usually conducted during winter and spring months, i.e., between November and April. The concentrations above the recommended criteria mainly occur during rains or freezing rain events with the application of deicing products or when the temperature is high enough to melt the roadside snow and ice through runoff into soils.

Besides concerns about chloride, acetate's potential ability to decrease available oxygen in surface water leads to additional environmental concerns. Acetate is assimilated rapidly as carbon resource for bacteria, and CMA or KAc used in highways increase the concentration of acetate above natural levels. Acetate based chemicals should be avoid in the following scenarios: (1) diluting potential of runoff is low; (2) runoff could flow through road drains into common waterbody; and (3) receiving water bodies are close to roads; (4) water runoff is possible to move into ice covered waterbody that has low dissolved oxygen; (5) receiving water temperature is warm during late spring storm (Brenner & Horner, 1992).

Groundwater contamination induced by anti-icing or deicing products are related to the following factors: application rates of products, frequency of the precipitation, characteristics of soil, distances between groundwater and roadway, permeability of aquifer material, direction and flow rate of groundwater (D'Itri, 1992).

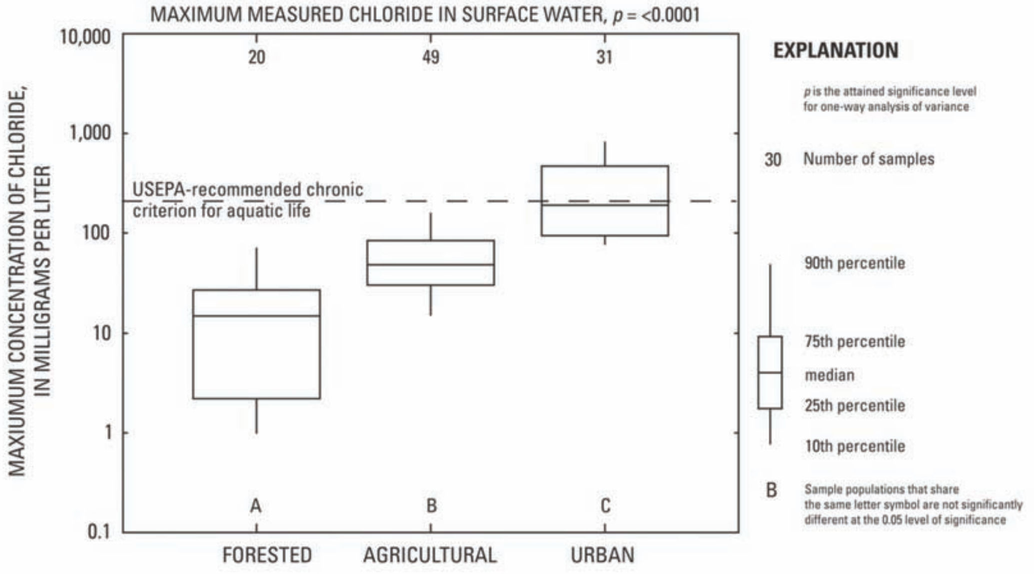

Figure 2.10 Distribution of maximum chloride concentration measured at selected surface water quality monitor stations in the glacial aquifer system, northern United States between 1991 and 2004 (Mullaney et al., 2009).

The hydrological cycle affecting road salt entering groundwater is well studied and can be described with the following equation:

$$P = RO + Re + ET + S$$

Where,
P = Precipitation;
RO = Runoff as stream flow (surface or direct runoff);
Re = Recharge or groundwater (groundwater discharge to stream as baseflow);
ET = Evaporation and plant transportation;
S = Storage in aquifers, streams, and reservoirs.

Only a portion of precipitation containing salts flows through soil zone, filtrates water table, and recharges groundwater. Most of precipitation run off in soils becomes saturated and enters drainage systems, ditches or storm system, watershed or other receiving waterbodies. If soils are not saturated, the portion of precipitation could not move through shallow soils and are absorbed by plants or released back to atmosphere via evaporation, while the portion of precipitation could flow through shallow soils above the water table as interflow, and eventually discharge as spring, seep, or stream baseflow.

In addition, long term exposure to sodium may increase hypertension (U.S. Environmental Protection Agency, 2003). Sodium ion's strong relationship with hypertension has influenced 12%–30% of Americans. Although sodium ion is not considered the only factor inducing hypertension, studies have shown that excess sodium lead to high blood pressure, which could increase the possibility of hypertension. The only federal drinking water standard for sodium is an unenforceable Drinking Water Advisory of 20 mg/L and 500 mg/day per person. The American Health Association (AHA) recommends that individual having high possibility of getting cardiovascular diseases or hypertension should not consume water with sodium concentration exceeding 20 mg/L. However, sodium concentration in 57.1% of urban land-use wells, 16.7% of agriculture land-use wells, and 8.0% of forested land-use wells were equal to or greater than 20 mg/L (Figure 2.11). Sodium ion has a positive charge and can be absorbed by negatively charged surface materials, such as minerals and clays. The proportion of sodium appearing in the groundwater strongly depends on the characteristics of soils.

2.2.3 Watershed

Indiana has 62,547 miles of rivers, ditches, and drainage ways and more than 1,500 lakes, reservoirs, and ponds (Indiana Department of Environmental Management, 2018) and therefore environmental impact of deicing chemicals on watersheds in Indiana should be evaluated. Water quality data from 57 Indiana Fixed Station Monitoring Program (FSMP) sites and nearby U.S. Geological Survey stream gages have been examined for 11 years between 2000 and 2010 (Figure 2.12). In general, chloride concentrations in Indiana were within acceptable ranges. Two main sources of chlorine include disinfectant used for water and wastewater treatment and chloride salts used in water softening or deicing processes. The chloride concentration trend was established and fell within acceptable ranges of local standards and criteria in more than 97% of collected samples (Figure 2.13). The maximum chloride concentration was 615 mg/L, and the 75th percentile was 51 mg/L (Risch et al., 2010). Elevated chloride concentrations were observed in four basins, in which three of them were in the Indianapolis area of the West Fork White River Basin. For Lake Michigan Basin, chloride criterion was 680 mg/L, while EPA recommended water-quality criterion for chloride is 230 mg/L. Significant decreasing trends were observed in six basins, in which two largest decreases were in the Lack Michigan Basin and eight sites in the Upper Wabash River Basin.

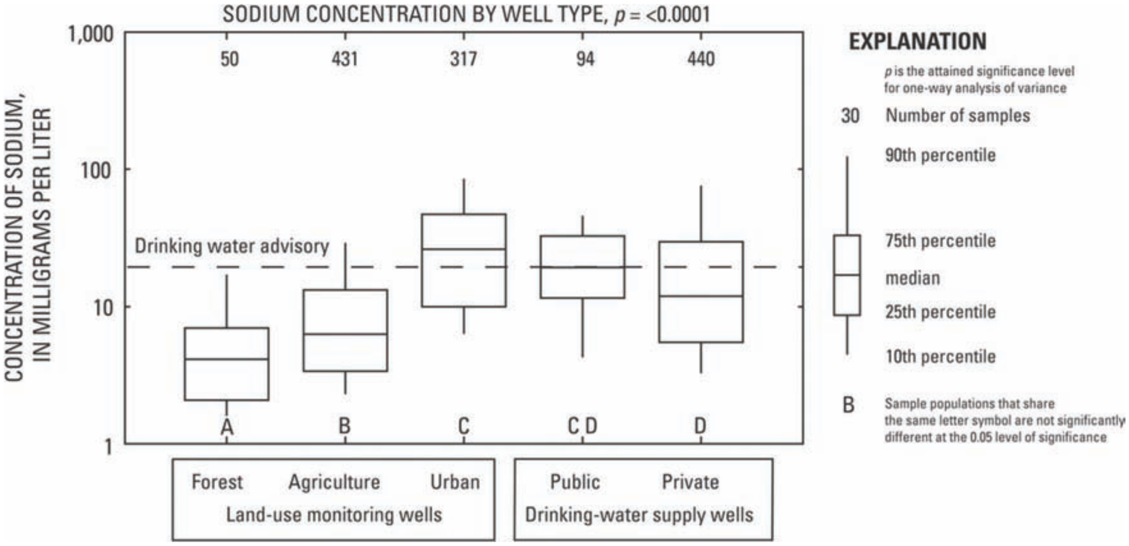

Figure 2.11 Distribution of sodium concentrations monitoring wells in forested, agricultural, and urban areas and in drinking-water supply wells in northern United States between 1991 and 2003 (Mullaney et al., 2009).

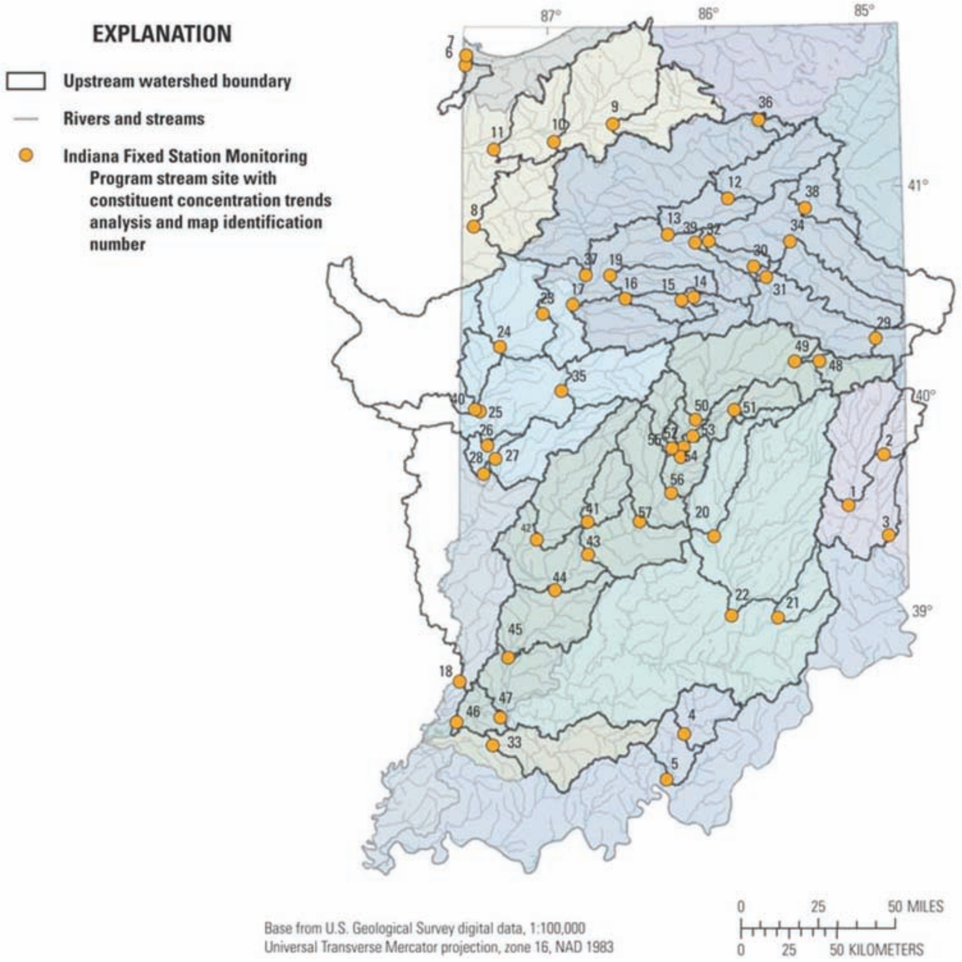

Figure 2.12 Indiana Fixed Station Monitoring Program stream site and upstream watershed (Risch et al., 2010).

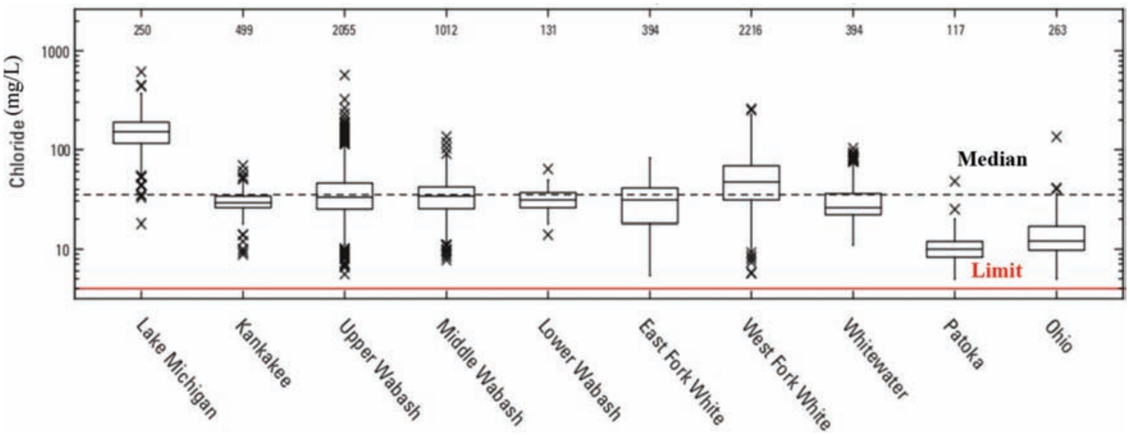

Figure 2.13 Chloride concentrations in Indiana streams between 2000 and 2010 (Risch et al., 2010).

Chloride could disrupt the natural metabolic processes of aquatic organisms. The regulation of stressors to aquatic lives and identification of potential chloride impact for fish and macroinvertebrate communities are important for watershed protection. A key factor in evaluating impact from chloride is the timing of peak concentration. Fish and macroinvertebrate spawn in cold temperature from late April to August depending on the water temperature, which may overlap with the high concentration of chloride, and therefore better management of deicing chemicals could help protect aquatic organisms.

Because the amount of road salt application varies as a function of local weather conditions and road authority's salt application policies, it is difficult to draw a conclusion on whether or not changes in application rate of deicing chemicals will mitigate their impacts on watersheds. Based on actual performance of deicing chemicals, winter operations managers can use less salts under similar winter weather conditions to minimize their environment impacts.

With Best Management Practices (BMP), winter maintenance operators could reduce road salt application to protect environmental health. BMP mainly focuses on the tool for optimizing the road salt use; improvement of equipment operation and awareness of public; and implementation of new technologies and novel products, such as alternative products (Nixon & DeVries, 2015). In addition, it is helpful to identify critical areas within a watershed that are most vulnerable to highest load to the instream and implement a paired sub-watershed study to assess the potential effects and cost-effectiveness using an alternative deicing chemical rather than traditional sodium chloride (Wenck Associates Inc., 2006). The alternative chemicals, however, may have their own problems. For example, sugar in beet juice may attract unwanted nuisance pests in the stream.

2.2.4 Vegetation

The adverse effects of anti-icing and deicing chemicals on vegetation along roadsides have been investigated, and the common chemical effects of vegetation include browning of leaves and impede photosynthesis, premature defoliation, suppressed bloom and fruit, and diminished regeneration and enhance mortality.

Plant response to salt stress can be partially explained by high salinity imposed by salt chemicals and osmotic stress (Niu et al., 1995), except that sodium is not a threat for halophytes, which live in salt marshes and sea coasts and could prevent accumulation of sodium in the cytoplasm via restricting uptakes across the plasma member and promoting extrusion or sequestration in halophytes (Hasegawa et al., 2000). Salt concentration over 400 mM can inhibit most enzyme activities and perturbate hydrophobic-electrostatic balance among forces maintaining protein structure (Serrano, 1996). Furthermore, sodium induced toxicity does not limit to toxic effects of sodium ions in the cytosol, potassium ions homeostasis could be disrupted because of competition between Na^+ and K^+ (Bartels & Sunkar, 2005). The increased salinization of roadside soils promotes the growth and spread of salt tolerant non-native species. The spread of halophytic species have been reported along sideroad in snow affected areas, such as northeastern U.S. and southern Canada (Canadian Environmental Protection Act, 2001). An uncovered salt pile of 10 years had an effect on endemic plant community of Pinhook bog, Indiana lead to an average concentration of 568 mg/L sodium and 1,215 mg/L chloride and resulted in the absence of all endemic species and the dominance of invaded non-native species *Typha angusifolia*. But after the salt pile was covered and shut down, salt concentration in interstitial water decreased by 50% in four years with the recurrence of many endemic species (Wilcox, 1986). Deicing chemicals decrease species diversity and evenness of fungal population and lead to significant decreasing of Shannon diversity of in upper soil layer (0–15 cm) (Ke et al., 2013).

CMA is thought to be harmless to terrestrial vegetation, and Mg^{2+} and Ca^{2+} have stimulating effects on some species. Widely applied CMA did not significantly affect yield, cover, vigor or rooting in herbaceous and woody plants. A previous study showed that 2,500 mg/L CMA, whose concentration was higher than that used in possible routine deicing application, was much less harmful than NaCl around the root zone during spreading and flooding (Brenner & Horner, 1992).

2.2.5 Wildlife

2.2.5.1 Amphibians. Amphibians are vulnerable to high salinity because their skins have critical functions for osmoregulation, which is a process to help organisms maintain internal solute concentration. Salinization of wetlands becomes a global concern because of application of road anti-icing and deicing products, intensive irrigation practices, and saltwater intrusion due to sea-level rise (Karraker et al., 2010). In amphibian embryos, breeding or placing their babies near or on the bottom of the pond faces the highest risk of road salts and rates of mortality. Because normal development depends on the exchange of freshwater via vitelline chamber, high salinities may result in impaired development and potential abnormalities. Amphibians' responses to high salinity are not direct mortality, but subtle effects, such as malformation in green frogs. In addition, several studies have shown that increased salinity has negative effects on other amphibians, such as decreased survival rate and sizes in spadefoot toads (Stănescu et al., 2016), survival and metamorphosis of frog's tadpoles (Hsu et al., 2012; Karraker et al., 2010).

In Indiana, North America Amphibian Monitoring Program (NAAMP) cooperated with Wildlife Diversity Section of Indiana Department of Natural Resources' Division of Fish and Wildlife and published distribution maps for amphibian species to help the general public to understand breeding chronology (Klueh, 2011). A survey of 104 potential amphibian-breeding sites in northwest Indiana has been done in terms of the presence and abundance of amphibian, habitant parameters, and water chemistry (Brodman et al., 2003). The levels of dissolved chloride, hardness, alkalinity and other hydrological or geometrical variables have been identified as most important breeding site factors.

Saline solution could reach 200 meters from highway and into wetland to contaminate amphibian habitats (Karraker, 2007). Conductivity, which is an indicator for salt concentration, was 20 times higher in side-road than that in forested pool. Previous results showed that conductivity at 3,000 µS reduced the embryonic and larval survivorship for wood frogs and malformed embryos died within a week of hatching. Some larvae exhibited normal development initially but could have abnormal behaviors like erratic swimming. *Rana clamitans*, a green frog, showed relative higher tolerance to low and moderate concentrations of salts and less sensitivity than other North American amphibians. These results suggest that salt application near wetlands should be well controlled to protect amphibians from adverse influence and the potential declining of embryonic and larval survivorship should be addressed.

2.2.5.2 Mammals and birds. Mammals may face sodium deficit and are attracted to salts on the road (Schulkin, 1991). Some mammals, like moose, white tailed deer, and snowshoe rabbit, extend their homes to roadside pool to satisfy their demand of sodium (Canadian Environmental Protection Act, 2001; Leblond et al., 2007).

Mortality of birds can be indirectly caused by salts as the bird ate salts and were struck by vehicles (Mineau & Brownlee, 2005). Birds need salts to maintain their physiological need and small rocks, or grit, which are their primary tools for digestion. However, in some cases, high ingested toxicity could contribute to abnormal behaviors. Birds had been observed as fearless, or weak and flying slowly accompanied by tremors and partial paralysis (Mineau & Brownlee, 2005). Ingesting high amount of sodium impeded flying and perching abilities in the house sparrow (Bollinger et al., 2005).

Environmental impacts of anti-icing and deicing chemicals are summarized in Table 2.16.

2.3 Cost

2.3.1 Cost of Deicing Chemicals

Typical treatment cost for winter operations includes standard labor, overtime, and deicing chemicals. Denver, Colorado spent an annual labor cost of $4 million, overtime of $0.5 million, and deicing chemicals of $1.5 million for street maintenance (Kennedy, 2018). Liquid salts stay on the road with less mobility and bounce and scatter reduction. A previous study in Oregon Department of Transportation showed that the cost of solid deicing chemicals was $96 per lane mile and only $24 per lane mile for liquid deicing chemicals, and seasonal cost dropped from $5,200 per mile with solids to $2,500 per

TABLE 2.16
Summary of different anti-icing or deicing chemicals' environmental impact (Fay et al., 2015)

	Surface and Groundwater	Soil	Vegetation	Wildlife
Chloride ($NaCl$, $MgCl_2$, $CaCl_2$)	Cl, Na, Mg, and Ca are easily dissolved in the water and increase the hardness. The potential anoxic condition in the receiving waterbody.	Na and Cl accumulate in the soil, break the soil structure and increase the heavy metal concentration via cation exchange. Ca^{2+} and K^+ could enhance the stability and permeability of soil structure.	Foliage is subject to chloride resulting in leaf singe, browning, and senesce. The increased salinization gives the possibility to establish the salt tolerant and spreading of non-native species. Shifts in plant communities.	Deicer additive Cl has negatable effect until increases to extremely high concentration. Amphibian's respondence to high salinity have subtle effects, such as malformation, but usually leads to nonfatal risk. Ingestion of salts directly for birds or mammals could cause toxicity and abnormal behavior.
Acetates (CMA, KAc)	Exert additive BOD leading to dissolved oxygen (DO) reduction. Enhance turbidity and hardness. Potassium ion could cause potential eutrophication of water body.	Ca^{2+} and K^+ could enhance the stability and permeability of soil structure. Degradation of CMA cause potential pH increasing.	Negative effects are considered as neglectable. At the low concentration (500 ppm) could act as fertilizer. If additive chemicals cause high concentration of Ca^{2+} and K^+, deterioration like low germination rate and browning of leaf may appear.	Promote bacteria and algae growth. KAc has more toxicity than CMA.
Beet juice	Exert significantly temporary additive total organic materials leading to DO reduction.	The breading down process could cause temporary anaerobic soil condition.	N/A	N/A
Glycerol	Exert additive BOD in aquatic system.	Glycerol has minimal negative effects on soil's stability and permeability.	At high concentration, the adverse influence observed on metabolism on plant cell and inhibition on enzyme activities. The component of glycerol could be adsorbed by vegetation.	Glycerol acted as contraceptive chemicals resulting in diminishing fertility in fish. For other animals, potential scenario including renal failure, fatty liver, even death.

mile with liquids (Bagley & Williams, 2011). Furthermore, liquid salts could improve safety via preventing snow and ice accumulation, decreasing reaction time, leaving bare road for transportation, and reducing windshield damage claims. None of the liquid deicing chemicals (NaCl, $CaCl_2$, and $MgCl_2$) lost their capacity after 14 months of field storage, regardless of the storage condition (Shi et al., 2011). NaCl-based solid deicing chemicals did not lose its capacity over the 12 months of field storage based on key properties, such as performance parameters (characteristic temperature Tc for ice crystals to start to melt and ice melting capacity at 30°F) regardless of the storage condition (Shi et al., 2011).

Direct liquid application could be combined with other techniques to achieve better performance and cost-effectiveness. Three common combination techniques are used: (1) pre-wetting: liquid sprayed on salt at the spinner (5–10 gallon per ton); (2) treated salt: liquid benefits without the liquid infrastructure (5–10 gallon per ton); (3) slurries: new technique with higher liquid pre-wetting use on salt (10–30 gallon per ton) (Bagley & Williams, 2011).

2.3.2 Equipment

One of the most important tasks for winter road maintenance involves mechanical removal of snow and ice from roadways to ensure safe driving conditions, and cost saving can be achieved via the use of efficient mechanical removal equipment, reduction of purchasing anti-icing or deicing materials, and improved safety pavement conditions. For instance, if snow or ice could be removed through plowing before ice bonds to the pavement, the need for deicers could be significantly reduced. A study in Otterbuin Park, Quebec showed that a salt reduction of 73% was achieved after implementing effective plowing practices and training (Canadian Environmental Protection Act, 2001). Furthermore, once the temperature of pavement was below 10°F, NaCl deicing product became less effective at melting snow or ice and causes melting snow or ice to stick to the pavement (Akin et al., 2013). Therefore, plowing may be effective at low temperatures because of reduction cost of operator, fuel, and amount of products use (Akin et al., 2013). A cost and benefit analysis of various plowing techniques is shown in Table 2.17.

2.3.3 Common Accepted Performance Measures (CAPM)

Establishing outcome-based level-of-service (LOS) goals on the basis of road condition to achieve certain criteria is a common practice. A survey of 75 U.S. and international agencies or private survey firms shows a typology matrix of cost information of different performance measures (Figure 2.14). Over 70% of agencies use LOS goals to achieve road maintenance goals (Xu et al., 2017).

Material usage, equipment usage, cost of labor, storm severity, and friction are representative variables for cost analysis. The comparison results of the relative timeliness, reliability, and effectiveness of methods are shown in Figure 2.15.

The timeliness is considered as the most reliable method for performance measurement. However, equipment, labor and material cost are also important. Effectiveness offers a magnitude of metrics reflecting the performance. For example, friction is rated highly effective as it measures how well the operation enhances friction of the road surface. Storm severity is regarded as medium reliable and could be easily quantified to set up a LOS. Customer satisfaction is low in timeliness and medium in cost and reliability but is an urgent demand to measure performance based on input from customers. For example, Minnesota Department of

TABLE 2.17
Cost and benefit of various plowing techniques (Akin et al., 2013)

Techniques	Costs	Benefits	Reference
Using wider front plows and tow plows	Conversion to 14-ft plow $400/foot; Two plows reduce equipment investment by 20% to 30%	Reduced number of passes required; Fuel savings; Reduced labor required; Increased snow removal efficiency	(Lannert, 2008)
High speed snow plow	Potential roadside damage	Reduced chemical usage; Improved level of service due to flexible cutting edge	(Michigan Department of Transportation, 2011)
Use of underbody plows and improved overall plowing practices	Total costs including prewetting equipment: $53,700	Total savings from salt reduction $151,200	(Canadian Environmental Protection Act, 2001)
Tow plow	$93,000	20–30% savings; Plow 50% more miles; 6–7 years return on investment; Increased service life of 20–30 years compared to typical 12–15 years; Operates at 40% of the cost of standard plow	(Michigan Department of Transportation, 2011)

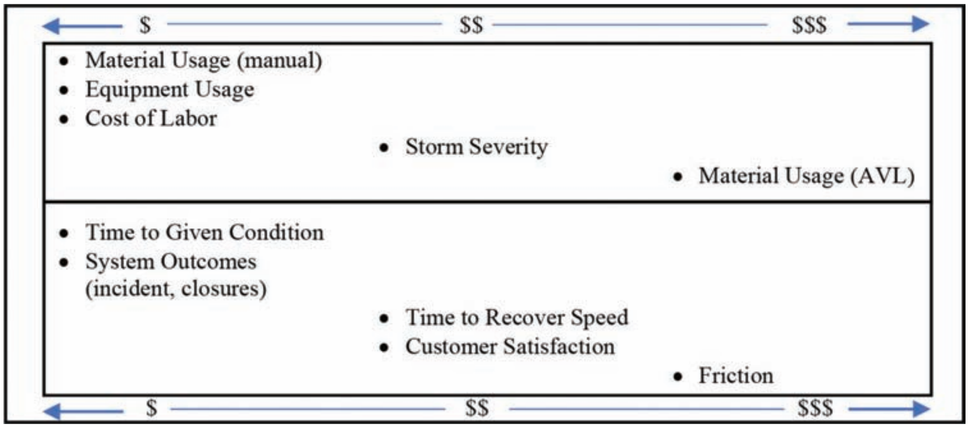

Figure 2.14 Cost of different performance measurements (Xu et al., 2017).

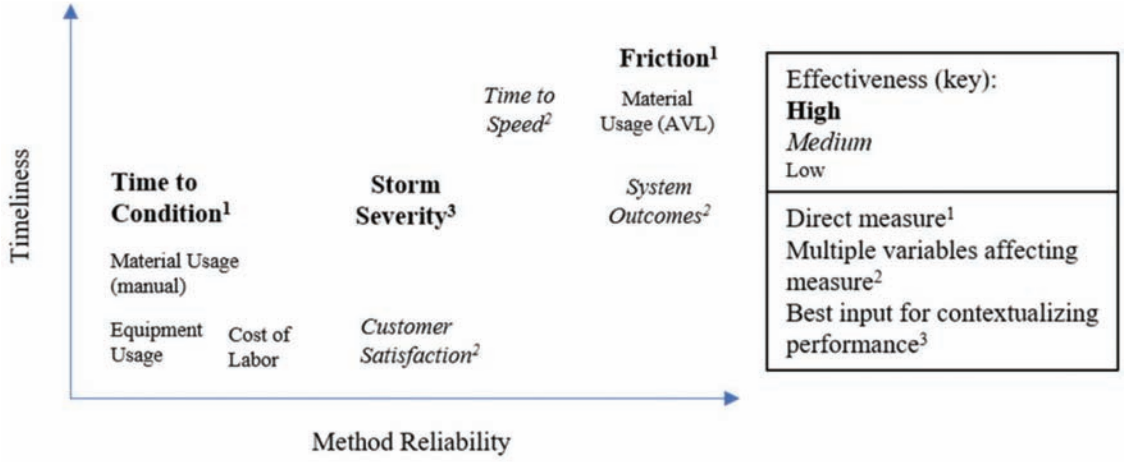

Figure 2.15 Performance by timeliness, reliability, and effectiveness (Xu et al., 2017).

Transportation shifted their bare pavement metric to bare line instead of full-width to match motorists' expectations (Xu et al., 2017).

3. LEVEL OF SERVICE ANALYSIS

3.1 Short-Term Cost Benefit Analysis

3.1.1 Product-Based Estimation

Costs of ten anti-icing or deicing products (four solid chemicals and six liquid chemicals) were evaluated and details of these products are listed in Table 3.1. Estimated application rates in terms of different temperature ranges are based on products' main components and the application rates are shown in Table 3.2 and Table 3.3. The temperature ranges are based on level of service established by INDOT (M. Anderson, personal communication, September 17, 2018). Further field studies can be to modify application rates for commercially available anti-icing or deicing products.

In addition, costs for the application of deicing chemicals are estimated. For solid deicing products, rock salt is the cheapest in different temperature ranges (Table 3.4). For liquid deicing products, sodium chloride brine is the cheapest (Table 3.5). The results also show that acetate-based products are cheaper than chloride-based products.

3.1.2 Weather-Based Estimation

Indiana is divided into four winter climatic zones (McCullouch, 2010). Southern zone has a milder winter temperature and a shorter winter season. Central zone is much colder with more frequent snow. Northern zone has a hasher temperature and experiences more snow events. Northern zone is divided into two distinct regions with one region at northwest corner under Lake Michigan with snowfall events twice as frequent as the rest of northern region and the other region not significantly affected by Lake Michigan. Four locations (Evansville, Fort Wayne, Indianapolis, and South Bend) were selected to represent four climatic zones at Indiana for southern zone, northeast zone, central zone; and northwest zone with lake effect snow, respectively.

The following equations provide estimations of winter index (WI) for four locations and Indiana (McCullouch,

TABLE 3.1
Costs of anti-icing or deicing products

Products		Manufacturer	Description	Price	Reference
Solid	Road salt	Cargill Salt	92~98% Sodium chloride	0.034 $/lbs	(Druschel, 2012)
	Clearlane enhanced	Cargill	90~92% Magnesium chloride	0.038 $/lbs	(Druschel, 2012)
	Ice slicer	Redmond Minerals	100% Calcium chloride	0.068 $/lbs	(Druschel, 2012)
Liquid	Road salt brine	Cargill Salt	23% Sodium chloride	0.16 $/gal	(Fischel, 2001)
	Caliber M1000	Minnesota Corn Processors	27% Magnesium chloride	0.55 $/gal	(Fischel, 2001)
	Liquidow armor	Dow Chemical	30% Calcium chloride	0.5 $/gal	(Fischel, 2001)
	Cf7	Cryotech	100% Potassium acetate	3.3 $/gal	(Fischel, 2001)
	Cma	Cryotech	32.6% Calcium magnesium acetate	5.49 $/gal	(Fischel, 2001)
	Unknown	Unknown	70/30 (w/w) 23% NaCl/beet juice	0.18 $/gal	(Fu et al., 2012)

TABLE 3.2
Solid deicing chemicals' application rate (lbs/lane-mile) in different temperature bands (Amsler, 2014; Nixon et al., 2007)

		Solid Deicing Chemicals' Application Rate (lbs/lane-mile)				
		Road Salt	Clearlane Enhanced	Ice Slicer	N/A	Cryotech CMA
Weather Category	Daily Road Temperature	92%–98% NaCl	90%–92% $MgCl_2$	100% $CaCl_2$	100% KAc	96% CMA
1	28–32+°F	100	110	90	168	170
2	20 to 27°F	250	275	232.5	385	400
3	10 to 19°F	350	374.5	308	490	525
4	10°F or below	>350	>360.5	>290.5	>455	>490

TABLE 3.3
Liquid deicing chemicals' application rate (lbs/lane-mile) in different temperature bands (Amsler, 2014; Fu et al., 2012; Nixon et al., 2007)

		Application Rate (lbs/lane-mile)					
Weather Category	Daily Road Temperature	Road Salt Brine 23% NaCl	Caliber M1000 27% $MgCl_2$	Liquidow Armor 30% $CaCl_2$	CF7 50% KAc	CMA 25% CMA	70/30 (w/w) 23% NaCl/Beet Juice
1	28–32+°F	44.4	32.2	33.3	32.0	18.1	100
2	20 to 27°F	111.0	83.2	83.3	73.3	42.8	250
3	10 to 19°F	155.4	110.2	113.5	93.3	56.0	350
4	10°F or below	>155.4	>106.5	>109.2	>86.7	>52.1	>350

2010). These equations are derived from multiple regression analysis in SAS, which is an interactive and batch program providing modules for statistics analysis. Weather data is collected from the National Oceanic and Atmospheric Administration (NOAA) for four winters (months—November through March, for the winter seasons of 2002–2003, 2001–2002, 2000–2001, 1999–2000).

Evansville: WI = 0.01116 Frost + 23.68383 Freezing_Rain + 43.46891 Drifting – 18.77938 × Snow + 63.02214 Snow_Depth + 0.23399 Hour – 0.32291 Average_Temperature

Fort Wayne: WI = 7.05832 Frost – 16.21024 Freezing_Rain + 6.31394 Drifting + 31.24970 Snow + 25.36240 Snow_Depth + 1.23828 Hour – 6.95440 Average_Temperature

TABLE 3.4
Solid deicing chemicals' cost (dollars/lane-mile) in different temperature bands (Amsler, 2014; Nixon et al., 2007)

		Solid Deicing Chemicals' Cost (dollars/lane-mile)				
Weather Category	**Daily Road Temperature**	**Road Salt 92%–98% NaCl**	**Clearlane Enhanced 90–92% $MgCl_2$**	**Ice Slicer 100% $CaCl_2$**	**Cryotech CMA 96% CMA**	**Road Salt Minimum Cost ($/lane-mile)**
1	28–32+°F	3.4	4.18	6.12	246.5	3.4
2	20 to 27°F	8.5	10.45	15.81	580.00	8.5
3	10 to 19°F	11.9	14.23	20.944	761.25	11.9
4	10°F or below	>11.9	>13.70	>19.754	>710.50	>11.9

TABLE 3.5
Liquid deicing chemicals' cost (dollars/lane-mile) in different temperature bands (Amsler, 2014; Fu et al., 2012; Nixon et al., 2007)

		Liquid Deicing Chemicals' Cost (dollars/lane-mile)						
Weather Category	**Daily Road Temperature**	**Sodium Chloride Brine 23% $NaCl_2$**	**Caliber M1000 27% $MgCl_2$**	**Liquidow Armor 30% $CaCl_2$**	**CF7 50% KAc**	**CMA 32.6% CMA**	**Unknown 70/30 (W/W) 23% $NaCl_2$/ Beet Juice**	**Road Salt Minimum Cost**
1	28–32+°F	7.11	17.71	16.67	105.60	99.43	7.99	3.4
2	20 to 27°F	17.76	45.76	41.67	242.00	234.85	19.98	8.5
3	10 to 19°F	24.87	60.62	56.74	308.00	307.44	27.98	11.9
4	10°F or below	24.87	58.55	54.62	286.00	286.09	27.98	11.9

Indianapolis: WI = 3.42152 Frost + 7.96888 Freezing_Rain + 7.24260 Drifting + 14.044284 Snow + 16.63333 Snow_Depth + 1.50251 Hour – 3.90486 Average_Temperature

South Bend: WI = -5.98483 Frost + 13.73518 Freezing_Rain + 12.57288 Drifting – 25.18103 Snow + 28.78145 Snow_Depth + 4.29121 Hour + 6.77877 Average_Temperature

Indiana: WI = 0.71839 Frost + 16.87634 Freezing_Rain + 12.90112 Drifting – 0.32281 Snow + 25.72981 Snow_Depth + 3.23541 Hour – 2.80668 Average_Temperature

3.2 Level of Service Analysis

3.2.1 Level of Service in Indiana

Level of service (LOS) can help customers make informed decisions and improve cost-effectiveness of anti-icing and deicing chemicals. LOS proposed by INDOT includes four weather categories with two sub-categories that defines the expectations of road conditions during storm and post storms. INDOT primarily focuses on two weather categories, road temperature and wind speed (M. Anderson, personal communication, September 17, 2018). Results obtained from LOS analysis are listed as follows:

- agency snow and ice control policy,
- road classifications,
- traffic data,
- maintenance coverage time periods defined for various operations, including clean-up operations,
- equipment types and amounts,
- location of facilities,
- personnel rules and regulations,
- materials used, and
- special circumstances and conditions.

The requirement of different categories is shown in Table 3.6 and the definition of each category is listed as follows (M. Anderson, personal communication, September 17, 2018):

- Category 1 (green): the most optimal conditions to remove snow or ice.

This category requires the least amount of rescores. Clean-up operations need to be typically finished immediately after storm and require minimal post storm supervision.

- Category 2 (yellow): more difficult conditions to remove snow or ice.

This category requires increased resources to achieve same expectations as category 1. Clean-up operations typically need to be finished by the next day. Lingering effects after storm exist including snow pack, ice, blowing and drifting snow. Post storm supervision is necessary until condition improves.

- Category 3 (red): conditions are the push envelope for maintenance. Material usage increases significantly in this category. For example, to melt ¼ inch ice at 30°F, 1,779 pounds of salts are required for each lane mile. To melt the same amount of ice at 20°F, 15,810 pounds of salts are needed for lane mile, which are about 9 times higher than those needed at 20°F. Sunlight and traffic play an important role to clean up roads effectively. Post

TABLE 3.6
Level of service requirement in Indiana (M. Anderson, personal communication, September 17, 2018)

			Pavement Condition					
			During Storm			Post Storm		
Weather Category	Maximum Daily Road Temperature	Winds Speeds Category Adjustment	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
1	28–32+°F	15+mph	Partial	Partial	Partial	Bare	Bare	Bare
2	20–27°F	15+mph	Partial	Partial	Partial	Bare	Bare	Partial
3	10–19°F	N/A	Partial	Passible	Passible	Bare	Partial	Passible
4	<10°F	N/A	Passible	Passible	Passible	Partial[1]	Partial[1]	Passible

[1] Class 1 and Class 2 route with category 4 weather condition, operators should continue working to reduce or eliminate partial snow coverage.

TABLE 3.7
Guidance for level of service (M. Anderson, personal communication, September 17, 2018)

	Special Guidance			Recovery Time (hours)		
Weather Category	Activities	Note	Frost Prevention / Pretreatment Application	Class 1	Class 2	Class 3
1	Liquid routes, pre-treatment and material should be maximized to reduce post storm ahead	—	Yes	2	5	6
2	The amount of salts and pre-treatment should be reduced in areas with high possibility of blowing or drifting snow	Require overnight supervisor	Yes	4	7.5	9
3	Additive liquid salt brine when the pavement is below 17°F	Post storm clean-up of lower tier road should be limited to daylight	Caution	8	12.5	N/A
4	Routes that are lower than tier routes should be reduced to plow only	Post storm clean-up of lower tier road could be reduced until conditions improve	Not recommended	12	N/A	N/A

storm clean-up operation should be limited to daylight hours. Increased manpower is needed to supervise operations, such as blowing and drifting snow.

- Category 4 (gray): a condition that requires operation adjustment.

Extreme cold conditions add significant fatigue on employees and equipment. Common salts are ineffective in this category. Higher tier routes should take priority for continual operation until conditions change.

Clean-up activities begin at the end of each storm with identified service objectives. Typically, clean-up activities should be applied during working hours. However, clean-up activities may be postponed during overtime hours because of some circumstances, such as coming storm or sudden decreasing temperature. Clean-up activities include plowing, usage of material to deice from highway surface, plowing back shoulders, cross-overs and approaches, cleaning and opening of frozen drains, and equipment cleanup (Belter et al., 2009).

The recommendation operation for four weather categories are listed in Table 3.7.

Three classes of INDOT roadway are defined as follows (M. Anderson, personal communication, September 17, 2018):

- Class 1: Interstate routes and roadways with average daily traffic (ADT) volumes over 10,000 vehicles per day, as well as other high priority roadways including those serving hospital facilities and other emergency service providers.
- Class 2: Routes with traffic volumes between 5,000 and 10,000 ADT.
- Class 3: Routes with traffic volumes less than 5,000 ADT.

3.2.2 Traffic Condition

Common performance approaches for analyzing traffic condition include space mean speed, travel time, volume/capacity (V/C) ratio, and crash frequency. Space mean speed is the recommended variable to establish LOS based on traffic condition (Table 3.8). Travel time is equivalent to speed. V/C ratio could change during winter events and it is hard to be used as a parameter to set up a LOS for winter maintenance. Crash frequency was not correlated well with traffic conditions (McCullouch et al., 2013).

TABLE 3.8
Level of service based on traffic condition (McCullouch et al., 2013)

Traffic Speed (70 mph posted)	**>55**	**45–55**	**35–45**	**25–35**	**<25**
LOS grade	Very good	Good	Fair	Poor	Very poor

TABLE 3.9
Modified score for storm index factor (Nixon & Qiu, 2005)

	Freezing Rain	**Light Snow (<2 Inches)**	**Medium Snow (2–6 Inches)**	**Heavy Snow (>6 Inches)**
Storm Type (ST)	**0.4**	**0.35**	**0.52**	**1**
Storm temperature (T_i)	Warm (>32°F)	Midrange (25–32°F)	Cold (<10–25°F)	Extreme cold (<10°F)
	0.25	0.4	0.6	1
Wind condition in storm (W_i)	Light (<15 mph)	Strong (>15 mph)	—	—
	1	1.2	—	—
Early storm behavior (B_i)	Start at snow	Start at rain	—	—
	0	0.1	—	—
Post-storm temperature (T_p)	Same as in storm	Warming	Cooling	—
	0	-0.87	0.15	—
Post-storm wind condition (W_p)	Light (<15 mph)	Strong (>15 mph)	—	—
	0	0.25	—	—

Snow or ice removal performance varied because of vehicle speed. Base on the data collected between 2010 and 2012, winter storm performance standard has been proposed by INDOT as follows:

- For interstate road with ADT less or equal to 65,000 vehicle per day (VPD), less than 25% of total traffic speed was no more than 45 mph per storm event.
- For interstate road with ADT more than 65,000 VPD, less than 60% of total traffic speed was no more than 45 mph per storm event.

3.2.3 Weather Condition

The common weather conditions have been collected in Indiana. Currently, 29 road weather information system station provide on-line weather information in Indiana and includes pavement condition (wet or dry), pavement temperature, air temperature, dew point temperature, precipitation, wind speed, wind direction, subsurface temperature, and visual image. In addition, National Weather Service Data also collects weather (McCullouch et al., 2013).

Storm index has been proposed to evaluate weather condition. INDOT used weather hour to define maintenance severity. The storm index proposed by Nixon spans a wide applicable range of storm characteristics (Nixon & Qiu, 2005).

The equation to calculate storm severity index is shown as follows:

$$SSI = \left(\frac{1}{b} \times ST \times T_i \times W_i + B_i + T_p + W_p - a \right)^{0.5}$$

Where,

SSI = storm severity index;
ST = storm type;
T_i = in-storm road surface temperature;
W_i = in-storm wind condition;
B_i = early storm behaviors;
T_p = post-storm temperature;
W_p = post-storm wind condition;
a, b = parameters to normalize storm severity index from 0 to 1.

If calculated SSI is greater than 1, then SSI is assumed to be 1. If calculated SSI is less than 0, then SSI can be assumed to be 0. The scores used in the SSI calculation equation has been modified and listed in Table 3.9.

3.3 Bare Pavement Regain Time and Application Rate

For low volume transportation facilities, salt application rate, pavement surface temperature, and amount of snow have significant impacts on desirable bare pavement regain time (BPRT). Other weather conditions, such as air temperature, sky-view condition, humidity, wind speed, dew point, and wind chill, do not cause significant contributions to BPRT.

BPRT can be estimated using the following equation:

$$\text{BPRT (hour)} = b + k_1 \times \text{Salting rate (lb/1,000 ft}^2) + k_2 \times \text{Pavement surface temperature (°C)} + k_3 \times \text{Thickness of snow (cm)}$$

b_1 = intercept
k_1 = Coefficient of salting rate
k_2 = Coefficient of pavement surface temperature

TABLE 3.10
Parameter estimation of BPRT with multiple regression for salt and alternative products (Hossain et al., 2015; Hossain et al., 2014)

Salt	b	k_1	k_2	k_3
Rock salt	5.163	-0.081	-0.142	-0.916
Slicer	5.167	-0.221	-0.130	3.823
Blue	7.749	-0.256	-0.254	-2.689
Green	1.845	-0.054	-0.191	0.769
Jet blue	3.097	-0.093	-0.102	0.427
Salt (unknown)	3.339	-0.069	-0.476	0.571

k_3 = Coefficient of amount of snow

A multiple regression analysis was conducted and the results were shown in Table 3.10.

For normal volume transportation facilities, if application rate derived from field study for one alternative product is not available, the alternative product's application rate needs to be estimated based on melt capacity derived from experiments.

Assuming the performance of rock salt at 20°F as base standard, the performance of alternative product at 20°F can be estimated with the following equation:

$$\text{Application rate of a proposed deicer} = \frac{\text{Application rate of rock salt at } 20^\circ\text{F} \times \text{Ice melting capacity of rock salt at } 20^\circ\text{F}}{\text{Ice melt capacity of a proposed deicer at } 20^\circ\text{F}}$$

4. ENVIRONMENTAL IMPACT ANALYSIS

4.1 Life Cycle Assessment

Previous studies of environmental impacts mainly focus on one specific aspect after deicing chemicals have been applied, such as chloride concentration increase in soil after application (Ke et al., 2013). Life cycle assessment (LCA) is a technique to comprehensively quantify environmental impacts of ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, noncarcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion over the entire life cycle from resource extraction to end of life. Unlike full cost measurement including all infrastructure and environmental costs, LCA provides environmental consequences of different decisions (Fitch et al., 2013). However, limited studies have been done on LCA of deicing chemicals (Fitch et al., 2013).

In this study, LCA was conducted on two conventional deicing chemicals (NaCl and $CaCl_2$) and four alternative products (KAc, CMA, beet juice, and glycerin). In addition, application rate of deicing chemicals has been considered in this analysis. As using alternative products rather than conventional deicers may increase the application rate (Frischknecht et al., 2005), it is necessary to analyze the overall environmental impact of alternative deicing chemicals with similar deicing performance. The results of LCA were used to analyze the impacts of deicing chemicals at all lifecycle stages and determine which product has the least environmental impact. The results may help INDOT, chemical suppliers, and environmental scientists to evaluate various deicing chemicals to evaluate their environmental impacts.

TABLE 4.1
Data source of chemicals

Chemicals	Data Source
NaCl	(Frischknecht et al., 2005)
$CaCl_2$	(Frischknecht et al., 2005)
KAc	(Himmrich et al., 1995)
CMA	(Warner, 2016)
Beet juice	(Frischknecht et al., 2005)
Glycerin	(Frischknecht et al., 2005)

Life cycle inventory analysis for NaCl, $CaCl_2$, and glycerin has been established in the United States and related data are available in the ecoinvent database in software SimaPro, a widely used LCA software. However, lifecycle inventory of KAc, CMA, and sugar beet are not available. Data sources of these six deicing chemicals are listed in Table 4.1. The system boundaries were established from acquisition of chemicals, transportation to storage, and application to the roadway. Transportation from storage place to applied place is not considered, as the impact resulted from transportation is considered as identical for each deicing chemical.

4.2 TRACI and Impact Assessment Categories

Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) is a framework developed and recommended by the U.S. Environmental Protection Agency's (EPA) National Risk Management Research Laboratory to assess environmental impacts (Bare & Science Applications International Corporation, 2003). TRACI can be used to compare the environmental and human preferability of two or more products (Bare & Science Applications International Corporation, 2003). TRACI includes chemical and environmental impact of ozone depletion, global warming, photochemical smog, acidification, eutrophication, human health cancer (carcinogenics), human health noncancer (noncarcinogenics), human health criteria (respiratory effects), ecotoxicity, and fossil fuel depletion (Bare & Science Applications International Corporation, 2003).

Environmental impact of ozone depletion is evaluated based on the emission of chlorofluorocarbons (CFCs) or trichlorofluoromethane, which are substances that lead to decrease of the stratospheric ozone level. Ozone depletion may result in higher frequency of skin cancers and cataracts in the human population. Sources of CFCs include refrigerants, foam blowing agents, solvent, and halons (fire extinguishing agents). Ozone depletion potential (ODP) is a parameter proposed by the World Meteorological Organization

(WMO) to calculate substances that significantly result in breakdown of the ozone layer (World Meteorological Organization, 1999). Within TRACI 2.1, the most recent ODPs of deicing chemicals were used for each substance.

Global warming indicates the average increased temperature in the atmosphere near the Earth's surface and in the troposphere. Increasing temperature results in changes in global climate patterns. The warming emphasizes the consequences due to increased greenhouse gas emission from human activities. TRACI 2.1 utilizes global warming potential (GWPs) to calculate the potency of greenhouse gases relative to carbon dioxide.

Photochemical smog formation is another environmental impact included in TRACI. Ozone near the ground is created by multiple chemical reactions between nitrogen oxides (NOx) and volatile organic compounds (VOCs) in the presence of sunlight. The primary sources of smog formation are vehicles, electric power utilities, and industrial facilities. Carter's maximum incremental reactivity (MIR) was used in the analysis as it is a comprehensive model including human and environmental effects and is recommended by U.S. EPA (U.S. Environmental Protection Agency, 2005).

Acidification indicates increases concentration of hydrogen ion (H^+) in the environment. Acidification can be attributed to additive acids (e.g., nitric acid and sulfuric acid), additive substances (e.g., such as ammonia) in the water because of acid chemical reactions, biological activities, or natural environment, such as changes in soil due to increasing growth of local plant species (Bare et al., 2012). Acidification model in TRACI 2.1 does not incorporate characteristics of sites that may provide buffering capacity (Hauschild & Wenzel, 1998).

Eutrophication indicates an aquatic ecosystem with enriched nutrients (e.g., nitrates and phosphates) that can result in accelerated biological productivity, such as algae, weed, and undesirable accumulation of algal biomass (U.S. Environmental Protection Agency, 2008). Eutrophication model in TRACI 2.1 incorporates additional substances that have potential abilities to cause eutrophication (Bare et al., 2012).

According to current EPA regulations and concern of pollutants' characteristics, human health was represented by three categories in TRACI: carcinogenics, noncarcinogenics, and ecotoxicity. Input parameters of these categories were chosen based on EPA Risk Assessment Guidelines and Exposure Factors Handbook. The USEtox model adopts different model (e.g., CalTOX, impact 2002, USES-LCA, BETR, EDIP, WATSON, and EcoSense 2010) and is a comprehensive model for human health cancer and noncancer toxicity potentials and freshwater ecotoxicity potential for over 3,000 organic or inorganic substances (Hauschild et al., 2008; Rosenbaum et al., 2008).

Respiratory effect addresses a subset of criteria pollutants, such as particulate matter and precursors to particles. Particle matter refers to a collection of small particles in the air that cause human diseases including respiratory illness and death. Particle matter may be emitted particulates (primary particulates) or products from chemical reactions (secondary particulates), such as sulfur dioxide (SO_2) and nitrogen oxides (NOx). The sources of particle matter are fossil fuel combustion, wood combustion, and dust particles from road and field (Bare et al., 2012).

Resource depletion in TRACI 2.1 includes fossil fuel use, land use, and water use. Fossil fuel use has a non-site-specific recommendation in TRACI. Land use and water use categories are not fully established, although many studies have been done (Bare et al., 2003).

4.3 Environmental Impact Analysis

The environmental impact analysis was conducted with North American TRACI 2.1 (Version 1.04) with a normalization/weight set of U.S. 2008. The environmental analysis results are shown in Table 4.2 and the emission results are shown in Table 4.3.

The results of environmental impact data for the six evaluated deicing chemicals are shown in Table 4.4. Different units are used for different environmental impact categories. CFC-11 is trichlorofluoromethane or Freon 11, which is a widely used refrigerant. The number 11 indicates the number of atoms of carbon, hydrogen, fluorine, and chlorine. PM2.5 is fine particulate matter (PM2.5) that has a diameter of less than 2.5 micrometers. CTUe is comparative toxic unit for aquatic ecotoxicity impacts expresses the estimated potentially affected fraction of species integrated over time and the volume of the freshwater compartment, per unit of mass of the chemical emitted. CTUh is comparative toxic unit for human toxicity impacts expresses the estimated increase in morbidity (the number of disease cases) in the total human population per unit of mass of the chemical emitted. MJ surplus is megajoules of surplus, which measures the depletion of fossil fuel resources in terms of megajoules (MJ).

4.4 Case Study of Environmental Impact of Selected Products

To demonstrate how to apply the LCA results for environmental impact analysis of deicing chemicals, three products were selected (Table 4.5) and their environmental impact were calculated. The function unit in this study is based on melting one lane mile ice or snow on the road at 20°F. The environmental impact of each category calculated as the product of the dry salt application rate of each component (kg/mile) (Table 4.5) and corresponding environmental impact in each category (Table 4.4). The results are shown in Table 4.6 and Figure 4.1.

The environmental impact analysis for different products should be established based on different environmental categories. For example, if the applied deicers' environmental impact on surface water quality needs to be examined, then the category of eutrophication should be examined. Among the three tested

TABLE 4.2
Input of life cycle inventory data for 1 kg applied chemical

Inputs	NaCl	$CaCl_2$	KAc	CMA	Beet Juice	Glycerin	Unit	Unit Processes
Water	0.00256						m^3	Water, salt, sole
					6.444		m^3	Tap water, at user/US- US-EI U
	0.00382	0.051	0.138	0.1383		1.14	m^3	Water, unspecified natural origin, RER
Soda					0.002		kg	Soda, powder, at plant/US- US-EI U
Sodium chloride	1						kg	Sodium chloride as resource
		0.9571					kg	Sodium chloride, powder, at plant/US- US-EI U
Sodium methylate						0.0777	kg	Dummy_Sodium Methylate, at plant/kg/RNA
Sodium hydroxide						0.0033	kg	Sodium hydroxide, production mix, at plant/RNA
Potassium hydroxide			0.1535				kg	Potassium hydroxide | GLO market for | Conseq, U
Hydrochloric acid						0.146	kg	Hydrochloric Acid, at plant/kg/RNA
Phosphoric acid						0.0021	kg	Phosphoric Acid, at plant/kg/RNA
Citric acid						0.0025	kg	Dummy_Citric Acid, at plant/kg/RNA
Sulphuric acid					4E-04		kg	Sulphuric acid, liquid, at plant/US- US-EI U
Acetic acid			0.949	2.56			kg	Acetic acid, 98% in H2O, at plant/US- US-EI U
Organic chemicals	4.00E-10	3E-10	4.E-10	4.E-10	6E-04		p	Chemical factory, organics GLO | market for | Conseq, U
Inorganic chemicals					8E-04		kg	Chemicals inorganic, at plant/GLO US-EI U
Soybean oil						3.32	kg	Soybean oil, crude, degummed, at plant/kg/RNA
Sugar beets					5.846		kg	Sugar beets IP, at farm/US- US-EI U
Sugar					9E-11		p	Sugar refinery/GLO/I US-EI U
Methanol						0.305	kg	Methanol, at plant/RNA
Electricity	0.067	0.0255	0.2443	0.2443	0.191	0.12	kWh	Electricity, medium voltage (Trenouthet al., 2015) | market group for | Conseq, U
Heat	0.169		0.139	0.139	1.776		MJ	Heat, natural gas (Trenouthet al., 2015)| market group for | Conseq, U
	0.169		0.0563	0.056			MJ	Heat, heavy fuel oil, at industrial furnace 1MW/US- US-EI U
		4.607					MJ	Heat, at hard coal industrial furnace 1-10MW/US- US-EI U
Limestone		0.7657	0.083		0.176		kg	Limestone, at mine/US
Ammonia		0.0013					kg	Ammonia, liquid, at regional storehouse/US- US-EI U
Dolomitic lime				1.9134			kg	Dolomitic lime
Hard coal coke					0.015		MJ	Hard coal coke, at plant/US- US-EI U
Natural gas						0.0762	m3	Natural gas, combusted in industrial boiler/US
Transport during production					0.058		tkm	Transport, tractor and trailer/US- US-EI U
		0.0976					tkm	Transport, lorry >16t, fleet average/US- US-EI U
					0.01		tkm	Transport, lorry 20–28t, fleet average/US- US-EI U
					0.469		tkm	Transport, freight, rail/US- US-EI U
						1.24	tkm	Transport, combination truck, diesel powered/US

TABLE 4.3
Emission of life cycle inventory data for 1 kg applied chemical

Emissions		NaCl	$CaCl_2$	KAc	CMA	Beet Juice	Glycerin	Unit
Emissions to air	Heat, waste		0.0919	1.2	1.2	0.765		MJ
	Carbon dioxide, biogenic		0.0013			0.42		kg
	Ammonia		0.0013					kg
	Water	0.00131						m^3
Emissions to water	Water, RER	0.00507						m^3
	Fatty acids as C						0.0069	kg
	Nitrogen		0.0001					kg
	Phosphorus		3E-05					kg
	Calcium		0.0638					kg
	Cadmium		1E-07					kg
	Chloride		0.1531					kg
	Copper		1E-06					kg
	Mercury		1E-09					kg
	Nickel		7E-07					kg
	Lead		1E-05					kg
	Solids, inorganic		0.0634					kg
Waste to treatment	Disposal, limestone residue, 5% water, to inert material landfill/ US- US-EI U			1.2077		0.214		kg
	Treatment, sewage, from residence, to wastewater treatment, class 2/US- US-EI U					0.01		m^3
	Disposal, inert waste, 5% water, to inert material landfill/US- US-EI U		0.1595					kg

TABLE 4.4
Environmental impact data for one kilogram chemical applied

Categories	NaCl	$CaCl_2$	KAc	CMA	Beet Juice	Glycerin	Unit
Ozone depletion	8.09E-09	1.48E-07	2.87E-07	7.16E-07	1.68E-08	3.25E-08	kg CFC-11eq
Global warming	1.33E-01	3.76E-05	2.46E+00	8.25E+00	3.37E-01	6.52E-01	kg CO_2 eq
Smog	5.83E-03	3.73E-05	1.03E-01	2.84E-01	1.94E-02	3.76E-02	kg O_3 eq
Acidification	6.70E-04	9.06E-05	1.01E-02	3.08E-02	2.43E-03	4.69E-03	kg SO_2 eq
Eutrophication	1.97E-04	5.70E-05	1.83E-03	3.84E-03	2.37E-03	4.58E-03	kg N eq
Carcinogenics	5.38E-09	2.36E-04	2.56E-08	5.36E-08	-4.70E-09	-9.09E-09	CTUh
Noncarcinogenics	3.18E-08	1.12E-04	1.81E-07	5.38E-07	-2.76E-06	-5.34E-06	CTUh
Respiratory effects	7.79E-05	2.47E-05	1.24E-03	2.21E-03	1.59E-04	3.07E-04	kg $PM_{2.5}$ eq
Ecotoxicity	1.65E-01	4.01E-05	8.52E-01	1.90E+00	-1.54E+00	-2.97E+00	CTUe
Fossil fuel depletion	1.73E-01	2.51E-05	6.72E+00	1.71E+01	3.95E-01	7.64E-01	MJ surplus

TABLE 4.5
Products and dry salt application rates

Product	Component	Dry Salt Application Rate (kg/mile)	Reference
1	23% NaCl	30	(Fu et al., 2012)
2	30% beet juice + 70% salt brine	36 (10.8 beet juice and 25.5 NaCl)	(Fu et al., 2012)
3	30% $CaCl_2$	17	(Gerbino-Bevins, 2011)

products, product two has the highest impact on eutrophication (3.01×10^{-2} kg N eq) and product three has the lowest impact on eutrophication (9.69×10^{-4} kg N eq). However, when eco-toxicity is compared among the three products, product two has least impact on ecotoxicity (-1.21×10^{1} CTUe) and product three has highest impact on eco-toxicity (6.81×10^{-4} CTUe). This analysis showed that LCA can help winter operation operators to comprehensively and quantitatively evaluate environmental impacts of anti-icing and deicing chemicals in each of the ten environmental categories.

TABLE 4.6
Environmental impact data for one kilogram applied chemical

Category	**Product 1**	**Product 2**	**Product 3**	**Unit**
Ozone depletion	*2.43E-07*	3.84E-07	**2.52E-06**	kg CFC-11 eq
Global warming	3.98E+00	**6.96E+00**	*6.39E-04*	kg CO_2 eq
Smog	1.75E-01	**3.54E-01**	*6.34E-04*	kg O_3 eq
Acidification	2.01E-02	**4.28E-02**	*1.54E-03*	kg SO_2 eq
Eutrophication	5.90E-03	**3.01E-02**	*9.69E-04*	kg N eq
Carcinogenics	1.61E-07	*8.74E-08*	**4.00E-03**	CTUh
Noncarcinogenics	9.55E-07	*-2.84E-05*	**1.91E-03**	CTUh
Respiratory effects	2.34E-03	3.67E-03	*4.19E-04*	kg $PM_{2.5}$ eq
Ecotoxicity	**4.94E+00**	*-1.21E+01*	6.81E-04	CTUe
Fossil fuel depletion	5.20E+00	**8.61E+00**	*4.27E-04*	MJ surplus

Note: Highest environmental impact in each category is shown in **bold**. Lowest environmental impact is shown in *italics*.

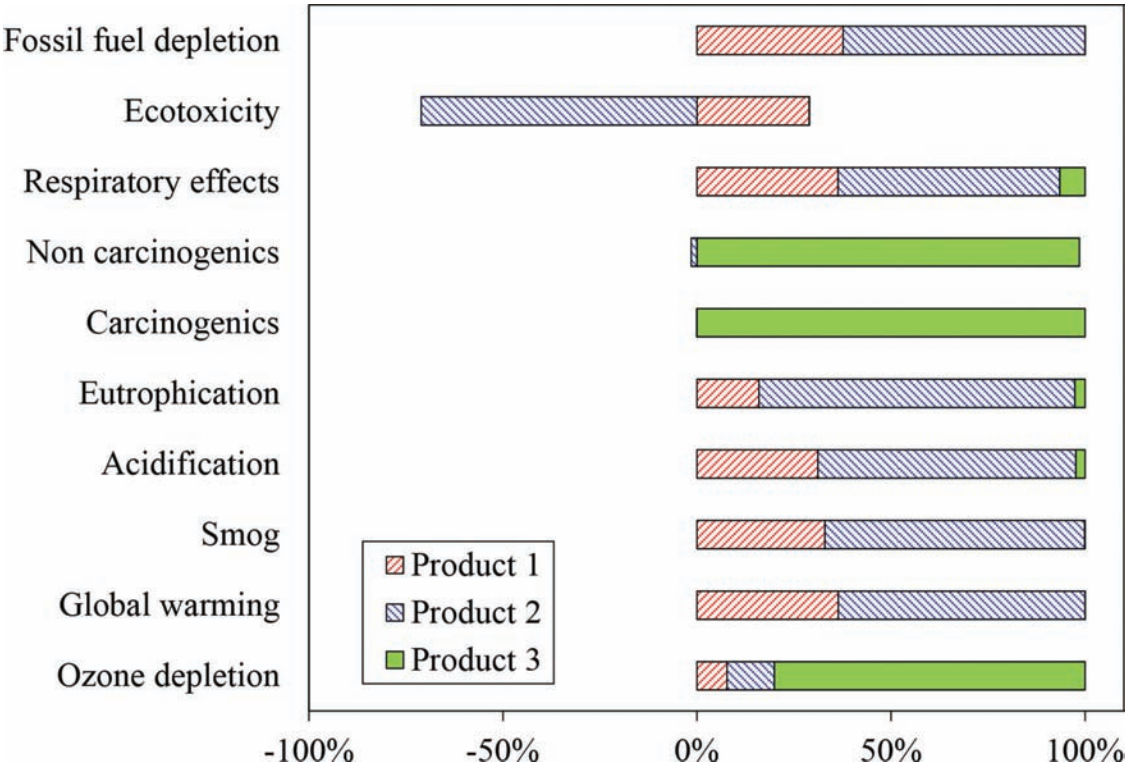

Figure 4.1 Relative environmental impact of products.

4.5 Decision Support Tool

A decision support tool has been developed to help winter operation managers to evaluate environmental impact of anti-icing and deicing chemicals to support decisions for snow and ice removal. The environmental impact is calculated with LCA software SimaPro with its package of North American TRACI 2.1 (Version 1.04) and normalization/weight set is U.S. 2008. The tool has been compiled with Microsoft Excel and can be easily updated.

There are eight tabs in the decision support tool file, which include a "State-Wide" tab, six individual tabs for six districts, and one "Predictive Tool" to predict and evaluate environmental impact of anti-icing and deicing chemicals for future application. The "State-wide" tab shows the summary information of state-wide chemical quantity, chemical cost, and environmental impact of deicing chemicals of the six districts of Indiana. There are six individual tabs and each of the six tabs represents a district in Indiana (Crawfordsville, Fort Wayne, Greenfield, LaPorte, Seymour, and Vincennes). The total lane mile in each district, actual used amount of different anti-icing and deicing chemicals, unit cost of each chemical, deck area, number of frost events, and application rates are input and chemical application rate (gals or lbs per lane mile) and each of the ten environment impacts are automatically calculated. Ten individual figures to show different environmental impact are automatically plotted based on the actual chemical

TABLE 4.7
Environmental impact of selected anti-icing and deicing chemicals

Environmental Impact	**Salt Brine**	**Liquid $CaCl_2$**	**Road Salt**	**Road Salt Treated**	
Application rate	**265 gals/mile**	**265 gals/mile**	**265 lbs/mile**	**265 lbs/lane mile**	**Unit**
Ozone depletion	2.19E-06	**5.87E-05**	*9.24E-07*	9.24E-07	kg CFC-11 eq
Global warming	**3.60E+01**	*1.49E-02*	1.52E+01	1.52E+01	kg CO_2 eq
Smog	**1.58E+00**	*1.48E-02*	6.66E-01	6.66E-01	kg O_3 eq
Acidification	**1.81E-01**	*3.59E-02*	7.65E-02	7.65E-02	kg SO_2 eq
Eutrophication	**5.33E-02**	*2.26E-02*	2.25E-02	2.25E-02	kg N eq
Carcinogenics	1.46E-06	**9.34E-02**	*6.14E-07*	6.14E-07	CTUh
Noncarcinogenics	8.62E-06	**4.45E-02**	*3.63E-06*	3.63E-06	CTUh
Respiratory effects	**2.11E-02**	9.78E-03	*8.90E-03*	8.90E-03	kg PM2.5 eq
Ecotoxicity	**4.46E+01**	*1.59E-02*	1.88E+01	1.88E+01	CTUe
Fossil fuel depletion	**4.69E+01**	*9.95E-03*	1.98E+01	1.98E+01	MJ surplus

Note: Highest environmental impact in each category is shown in **bold**. Lowest environmental impact is shown in *italics*.

quantify and environmental impact of each chemical in a specific district. The last tab in the decision support tool is a “Predictive Tool” to help winter operating managers better evaluate product costs and environmental impact. Application rates (gals or labs per mile) and unit cost of each chemical need to be manually updated and total chemical costs and chemical quantity can be automatically calculated. Ten individual figures to show different environmental impact are also automatically plotted based on the actual chemical quantify and environmental impact of each chemical.

For example, assuming a district uses one of the four deicing products (265 gals salt brine, 265 gals liquid $CaCl_2$, 265 lbs road salt, or 265 lbs road salt treated) for each lane mile for snow and ice control and their environmental impact are calculated in the “Predictive Tool” in the Decision Support Tool and the results are shown in Table 4.7. Out of the ten environmental impact categories, salt brine has highest environmental impact in seven categories (global warming, smog, acidification, eutrophication, respiratory effects, ecotoxicity, fossil fuel depletion). Liquid $CaCl_2$ has highest environmental impact in three categories (ozone depletion, carcinogenics, noncarcinogenics) and lowest environmental impact in six categories (global warming, smog, acidification, eutrophication, respiratory effects, ecotoxicity, fossil fuel depletion). Road salt has lowest environmental impact in four categories (ozone depletion, carcinogenics, noncarcinogenics, respiratory effects) and no high environmental impact. Neither highest nor lowest environmental impact is observed in road salt treated.

The information generated from the decision support tool can help winter operation managers compare and contrast different anti-icing and deicing chemicals to select the best product to minimize environmental impact. Although the ten environmental impacts cannot be directly compared as they describe different environmental impact, individual environmental impact can be selected to provide guidance to support product selection. Depending on the vicinity of highway and bridge decks to certain land use type, individual environmental impact of anti-icing and deicing chemicals can be compared to select the best product to protect the environment. For example, for highway and bridge decks close to agricultural sites that are already likely under impact of nutrient pollution, eutrophication should be minimized and therefore salt brine should not be selected among the four chemicals (Table 4.7) as it has the highest potential to result in eutrophication. For highway and bridge decks close to drinking water reservoirs, $CaCl_2$ should not be selected as it introduces most carcinogenics. For highway and bridge decks in urban areas, salt brine should be avoided as it will lead to smog issues. For urban areas with high population density, salt brine should be avoided as it will cause respiratory effects. These analyses have shown that the decision support tool can be a useful tool to help winter operation managers to make informed decisions to improve the selection of products based on their environmental effects.

5. CONCLUSIONS

The effectiveness, costs, and environmental impact of commonly used anti-icing and deicing chemicals were reviewed in this study. The results showed that many factors may contribute to the actual performance of anti-icing and deicing chemicals. Alternative products, such as beet juice, glycerol, and glycol were used as anti-icing and deicing chemicals and showed promising results for snow and ice control. Environmental impacts were reviewed as well. Soil, surface water, groundwater, watersheds, vegetation, and wildlife can be negatively affected by anti-icing and deicing chemicals and public health risks may increase. Concrete, bridges, pavement, and vehicles may be affected by anti-icing and deicing chemicals, and effects of chloride chemicals and acetate/formate based chemicals were different. Costs of anti-icing and deicing chemical were also reviewed.

Additionally, level of services was analyzed. Costs of anti-icing and deicing chemicals were compared and service categories and guidance for level of service were reviewed. Traffic condition and weather condition were reviewed, and calculation of bare pavement regain time and application were discussed.

Finally, life cycle assessment was used to quantify environmental impacts, such as global warming, acidification, eutrophication, and ecotoxicity, and environmental impact of two conventional deicers (NaCl and $CaCl_2$) and four alternative products (KAc, CMA, beet juice, and glycerin) were evaluated. For chloride-based deicers, calcium chloride has largest impacts on human health. Sugar beet, glycerin, and CMA have comparable or higher environmental impact, but have positive environmental impacts on eco-toxicity. A decision support tool was developed to evaluate environmental impact of all six districts in Indiana and environmental impacts in each of the ten environmental impact categories were compared. The predictive tool can help winter operation managers to make informed decisions to select best anti-icing and deicing chemicals to minimize environmental impact.

The knowledge reviewed in this study can help improve the understanding of the effectiveness, costs, and environmental effects of anti-icing and deicing chemicals. The newly developed life cycle assessment tool and decision support tool can help winter operating managers to better evaluate and select products with best benefit-cost ratio and lowest environmental impact for snow and ice control.

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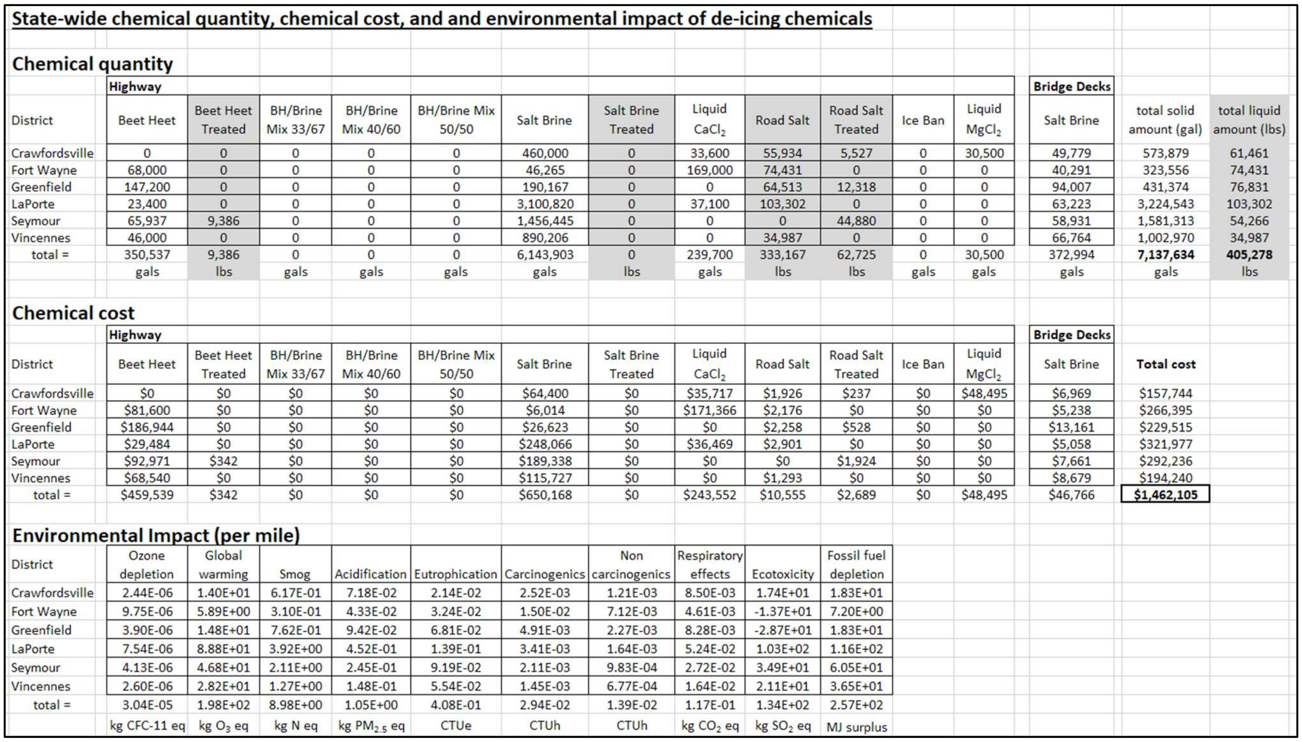
APPENDIX: USER MANUAL OF DECISION SUPPORT TOOL

APPENDIX: USER MANUAL OF DECISION SUPPORT TOOL

The decision support tool has been developed for the six districts in Indiana (Crawfordsville, Fort Wayne, Greenfield, LaPorte, Seymour, and Vincennes). Ten environmental impacts of varying levels and treatment types of each of the six districts have been evaluated.

There are eight tabs in the decision support tool file, which include a “State-Wide” tab, six individual tabs for six districts, and one “Predictive Tool” to predict and evaluate environmental impact of anti-icing and deicing chemicals for future application. The tool has been compiled with Microsoft Excel and can be easily updated by winter operation managers to support their decisions.

The first Excel tab “State-wide” shows the summary information of state-wide chemical quantity, chemical cost, and environmental impact of deicing chemicals of the six districts of Indiana (Figure A.1). There are three tables in this tab. The first table shows chemical quantity used in all six districts. Historically used deicing chemicals in each district are added up so the total amount of individual deicing chemicals is calculated. In addition to chemicals used in highway, chemical used on bridge decks are also calculated. The total amount of solid and liquid deicing chemicals is calculated individually. The second table shows chemical costs of each deicing chemicals in each district in both highway and bridge decks. The total chemical cost in each district is calculated and the state-wide cost for all the six districts is also calculated. The third table shows ten environmental impacts of deicing chemicals in each district and total environmental impact in all the six districts. The ten environmental impacts include ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, noncarcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion.



State-wide chemical quantity, chemical cost, and and environmental impact of de-icing chemicals

Chemical quantity

	Highway												Bridge Decks		
District	Beet Heet	Beet Heet Treated	BH/Brine Mix 33/67	BH/Brine Mix 40/60	BH/Brine Mix 50/50	Salt Brine	Salt Brine Treated	Liquid $CaCl_2$	Road Salt	Road Salt Treated	Ice Ban	Liquid $MgCl_2$	Salt Brine	total solid amount (gal)	total liquid amount (lbs)
Crawfordsville	0	0	0	0	0	460,000	0	33,600	55,934	5,527	0	30,500	49,779	573,879	61,461
Fort Wayne	68,000	0	0	0	0	46,265	0	169,000	74,431	0	0	0	40,291	323,556	74,431
Greenfield	147,200	0	0	0	0	190,167	0	0	64,513	12,318	0	0	94,007	431,374	76,831
LaPorte	23,400	0	0	0	0	3,100,820	0	37,100	103,302	0	0	0	63,223	3,224,543	103,302
Seymour	65,937	9,386	0	0	0	1,456,445	0	0	0	44,880	0	0	58,931	1,581,313	54,266
Vincennes	46,000	0	0	0	0	890,206	0	0	34,987	0	0	0	66,764	1,002,970	34,987
total =	350,537	9,386	0	0	0	6,143,903	0	239,700	333,167	62,725	0	30,500	372,994	**7,137,634**	**405,278**
	gals	lbs	gals	gals	gals	gals	lbs	gals	lbs	lbs	gals	gals	gals	gals	lbs

Chemical cost

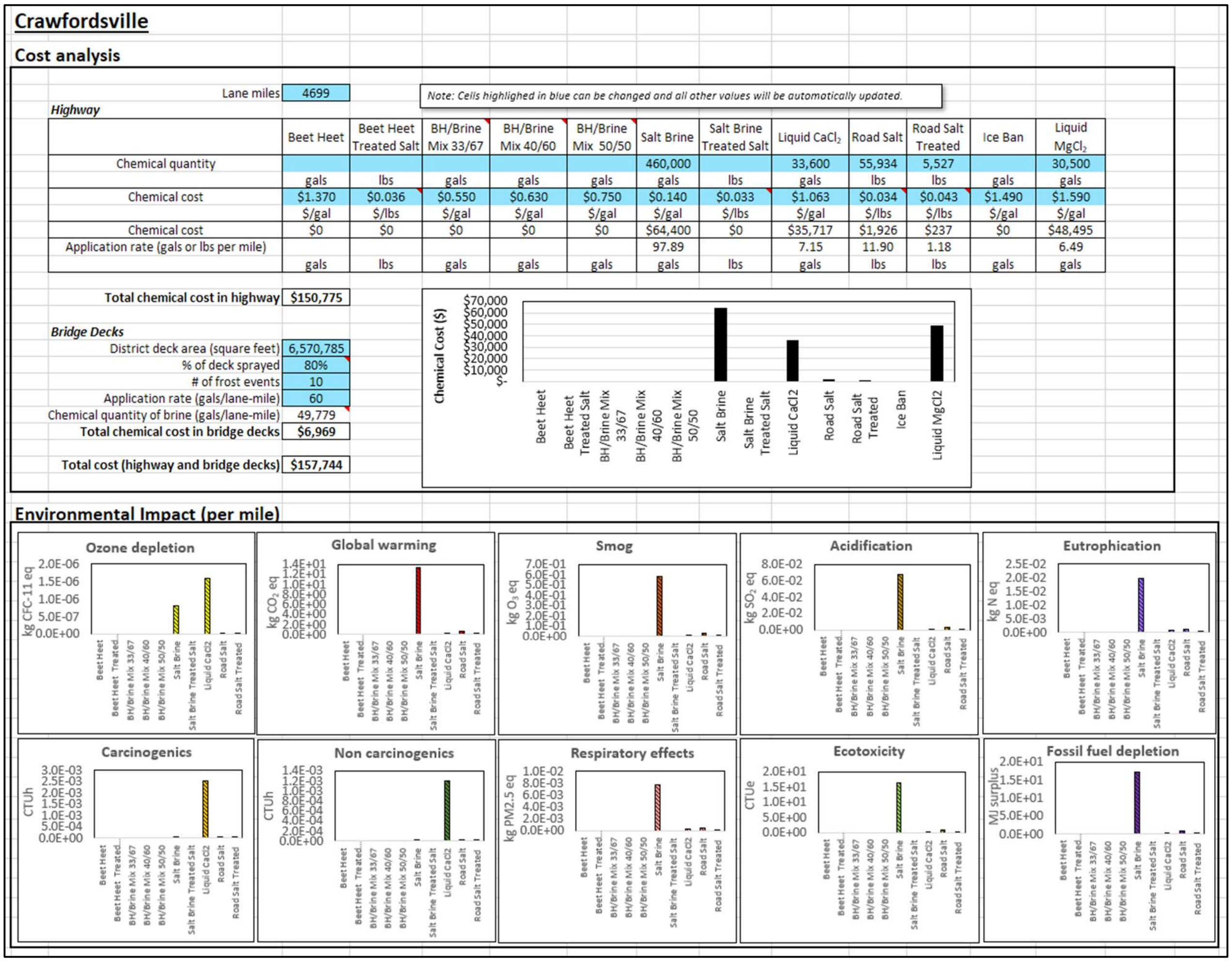
	Highway												Bridge Decks	
District	Beet Heet	Beet Heet Treated	BH/Brine Mix 33/67	BH/Brine Mix 40/60	BH/Brine Mix 50/50	Salt Brine	Salt Brine Treated	Liquid $CaCl_2$	Road Salt	Road Salt Treated	Ice Ban	Liquid $MgCl_2$	Salt Brine	**Total cost**
Crawfordsville	$0	$0	$0	$0	$0	$64,400	$0	$35,717	$1,926	$237	$0	$48,495	$6,969	$157,744
Fort Wayne	$81,600	$0	$0	$0	$0	$6,014	$0	$171,366	$2,176	$0	$0	$0	$5,238	$266,395
Greenfield	$186,944	$0	$0	$0	$0	$26,623	$0	$0	$2,258	$528	$0	$0	$13,161	$229,515
LaPorte	$29,484	$0	$0	$0	$0	$248,066	$0	$36,469	$2,901	$0	$0	$0	$5,058	$321,977
Seymour	$92,971	$342	$0	$0	$0	$189,338	$0	$0	$0	$1,924	$0	$0	$7,661	$292,236
Vincennes	$68,540	$0	$0	$0	$0	$115,727	$0	$0	$1,293	$0	$0	$0	$8,679	$194,240
total =	$459,539	$342	$0	$0	$0	$650,168	$0	$243,552	$10,555	$2,689	$0	$48,495	$46,766	**$1,462,105**

Environmental Impact (per mile)

District	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Crawfordsville	2.44E-06	1.40E+01	6.17E-01	7.18E-02	2.14E-02	2.52E-03	1.21E-03	8.50E-03	1.74E+01	1.83E+01
Fort Wayne	9.75E-06	5.89E+00	3.10E-01	4.33E-02	3.24E-02	1.50E-02	7.12E-03	4.61E-03	-1.37E+01	7.20E+00
Greenfield	3.90E-06	1.48E+01	7.62E-01	9.42E-02	6.81E-02	4.91E-03	2.27E-03	8.28E-03	-2.87E+01	1.83E+01
LaPorte	7.54E-06	8.88E+01	3.92E+00	4.52E-01	1.39E-01	3.41E-03	1.64E-03	5.24E-02	1.03E+02	1.16E+02
Seymour	4.13E-06	4.68E+01	2.11E+00	2.45E-01	9.19E-02	2.11E-03	9.83E-04	2.72E-02	3.49E+01	6.05E+01
Vincennes	2.60E-06	2.82E+01	1.27E+00	1.48E-01	5.54E-02	1.45E-03	6.77E-04	1.64E-02	2.11E+01	3.65E+01
total =	3.04E-05	1.98E+02	8.98E+00	1.05E+00	4.08E-01	2.94E-02	1.39E-02	1.17E-01	1.34E+02	2.57E+02
	kg CFC-11 eq	kg O_3 eq	kg N eq	kg $PM_{2.5}$ eq	CTUe	CTUh	CTUh	kg CO_2 eq	kg SO_2 eq	MJ surplus

Figure A.1 Screenshot of the decision support tool to calculate chemical cost and environmental impact.

In addition to the “State-wide” tab that can automatically calculate chemical quantity, cost, and environmental impact for all six districts, there are six individual tabs and each of the six tabs represents a district. For example, the tab “Crawfordsville” includes original data and results of cost analysis and environmental impact in the district of Crawfordsville (Figure A.2). The total lane mile in Crawfordsville District, actual used amount of different deicing chemicals, unit cost of each chemical, deck area, number of frost events, and application rates are input and chemical application rate (gals or lbs per lane mile) and each of the ten environment impacts are automatically calculated. A figure to compare total cost of different anti-icing and deicing chemicals is provided. Ten individual figures to show ten different environmental impact are automatically plotted based on the actual chemical quantify and environmental impact in a specific district.



Crawfordsville

Cost analysis

Lane miles: 4699

Note: Cells highlighed in blue can be changed and all other values will be automatically updated.

Highway

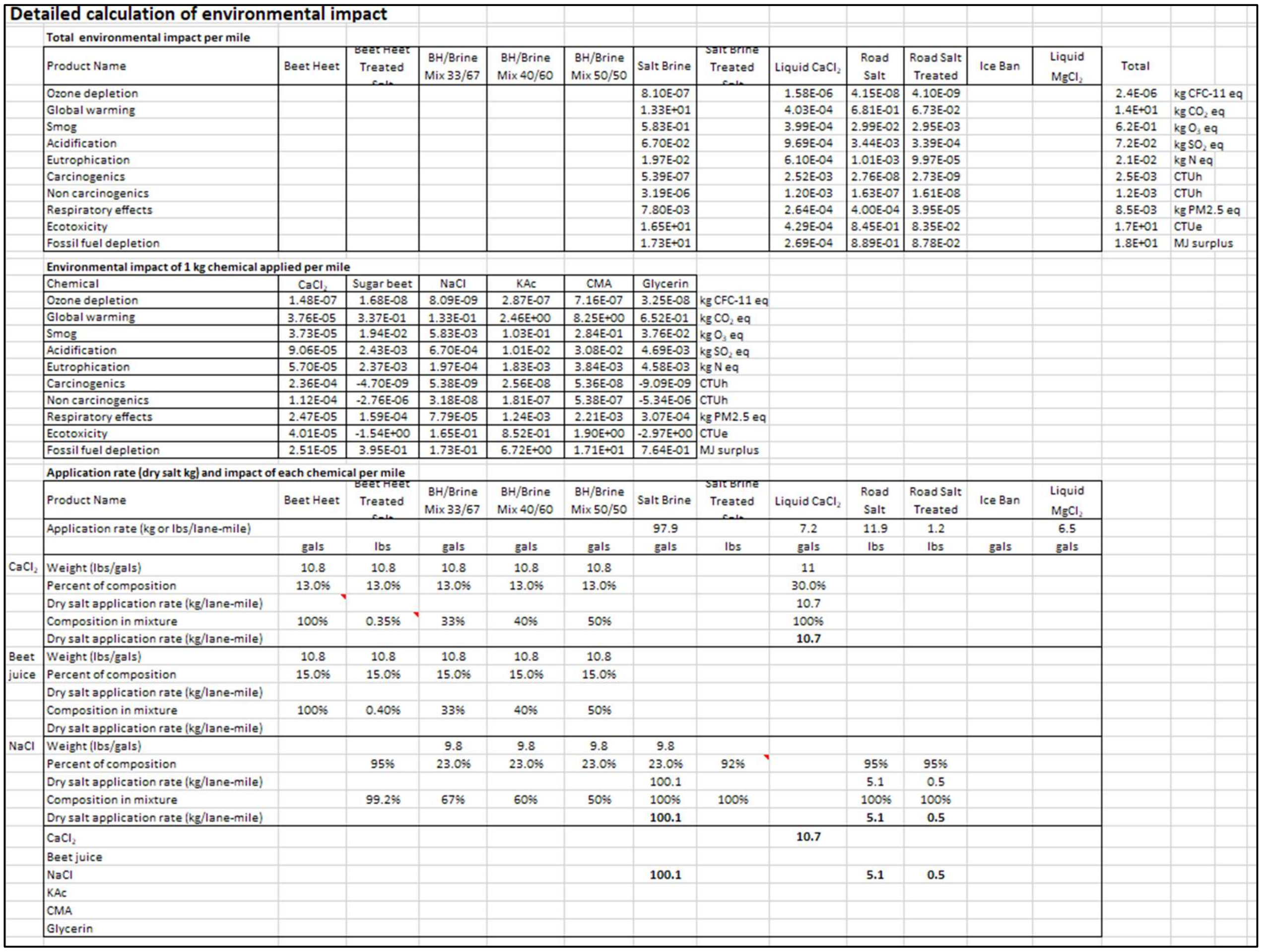
	Beet Heet	Beet Heet Treated Salt	BH/Brine Mix 33/67	BH/Brine Mix 40/60	BH/Brine Mix 50/50	Salt Brine	Salt Brine Treated Salt	Liquid $CaCl_2$	Road Salt	Road Salt Treated	Ice Ban	Liquid $MgCl_2$
Chemical quantity						460,000		33,600	55,934	5,527		30,500
	gals	lbs	gals	gals	gals	gals	lbs	gals	lbs	lbs	gals	gals
Chemical cost	$1.370	$0.036	$0.550	$0.630	$0.750	$0.140	$0.033	$1.063	$0.034	$0.043	$1.490	$1.590
	$/gal	$/lbs	$/gal	$/gal	$/gal	$/gal	$/lbs	$/gal	$/lbs	$/lbs	$/gal	$/gal
Chemical cost	$0	$0	$0	$0	$0	$64,400	$0	$35,717	$1,926	$237	$0	$48,495
Application rate (gals or lbs per mile)						97.89		7.15	11.90	1.18		6.49
	gals	lbs	gals	gals	gals	gals	lbs	gals	lbs	lbs	gals	gals

Total chemical cost in highway	**$150,775**
Bridge Decks	
District deck area (square feet)	6,570,785
% of deck sprayed	80%
# of frost events	10
Application rate (gals/lane-mile)	60
Chemical quantity of brine (gals/lane-mile)	49,779
Total chemical cost in bridge decks	**$6,969**
Total cost (highway and bridge decks)	**$157,744**

Figure A.2 Screenshot of cost analysis and environmental impact in Crawfordsville.

Below the cost analysis figure and ten environmental impact figures, the detailed data on the calculation of environment are provided (Figure A.3). In this section, the first table shows individual environmental impact of each deicing chemical, which are calculated based on environmental impact of one kg chemical applied per mile. The table at the bottom shows application rate (dry salt kg) and impact of each chemical per mile. The composition of each deicing product is included in the analysis and percent of composition of deicing chemical is also included to calculate the actual amount of chemicals applied each mile. Certain products, such as Beet Heet/Brine Mix 33/67, are mixtures of two or more products and composition in mixture is considered. The final result of total environmental impact per mile is calculated and used to plot the figures at the bottom of Figure A.2.

All the data in this tab are automatically calculated and the results are fed to the "State-wide" tab, except for the cells highlighted in light blue color, which should be updated manually.



Detailed calculation of environmental impact

Total environmental impact per mile

Product Name	Beet Heet	Beet Heet Treated	BH/Brine Mix 33/67	BH/Brine Mix 40/60	BH/Brine Mix 50/50	Salt Brine	Salt Brine Treated	Liquid $CaCl_2$	Road Salt	Road Salt Treated	Ice Ban	Liquid $MgCl_2$	Total	
Ozone depletion						8.10E-07		1.58E-06	4.15E-08	4.10E-09			2.4E-06	kg CFC-11 eq
Global warming						1.33E+01		4.03E-04	6.81E-01	6.73E-02			1.4E+01	kg CO_2 eq
Smog						5.83E-01		3.99E-04	2.99E-02	2.95E-03			6.2E-01	kg O_3 eq
Acidification						6.70E-02		9.69E-04	3.44E-03	3.39E-04			7.2E-02	kg SO_2 eq
Eutrophication						1.97E-02		6.10E-04	1.01E-03	9.97E-05			2.1E-02	kg N eq
Carcinogenics						5.39E-07		2.52E-03	2.76E-08	2.73E-09			2.5E-03	CTUh
Non carcinogenics						3.19E-06		1.20E-03	1.63E-07	1.61E-08			1.2E-03	CTUh
Respiratory effects						7.80E-03		2.64E-04	4.00E-04	3.95E-05			8.5E-03	kg PM2.5 eq
Ecotoxicity						1.65E+01		4.29E-04	8.45E-01	8.35E-02			1.7E+01	CTUe
Fossil fuel depletion						1.73E+01		2.69E-04	8.89E-01	8.78E-02			1.8E+01	MJ surplus

Environmental impact of 1 kg chemical applied per mile

Chemical	$CaCl_2$	Sugar beet	NaCl	KAc	CMA	Glycerin	
Ozone depletion	1.48E-07	1.68E-08	8.09E-09	2.87E-07	7.16E-07	3.25E-08	kg CFC-11 eq
Global warming	3.76E-05	3.37E-01	1.33E-01	2.46E+00	8.25E+00	6.52E-01	kg CO_2 eq
Smog	3.73E-05	1.94E-02	5.83E-03	1.03E-01	2.84E-01	3.76E-02	kg O_3 eq
Acidification	9.06E-05	2.43E-03	6.70E-04	1.01E-02	3.08E-02	4.69E-03	kg SO_2 eq
Eutrophication	5.70E-05	2.37E-03	1.97E-04	1.83E-03	3.84E-03	4.58E-03	kg N eq
Carcinogenics	2.36E-04	-4.70E-09	5.38E-09	2.56E-08	5.36E-08	-9.09E-09	CTUh
Non carcinogenics	1.12E-04	-2.76E-06	3.18E-08	1.81E-07	5.38E-07	-5.34E-06	CTUh
Respiratory effects	2.47E-05	1.59E-04	7.79E-05	1.24E-03	2.21E-03	3.07E-04	kg PM2.5 eq
Ecotoxicity	4.01E-05	-1.54E+00	1.65E-01	8.52E-01	1.90E+00	-2.97E+00	CTUe
Fossil fuel depletion	2.51E-05	3.95E-01	1.73E-01	6.72E+00	1.71E+01	7.64E-01	MJ surplus

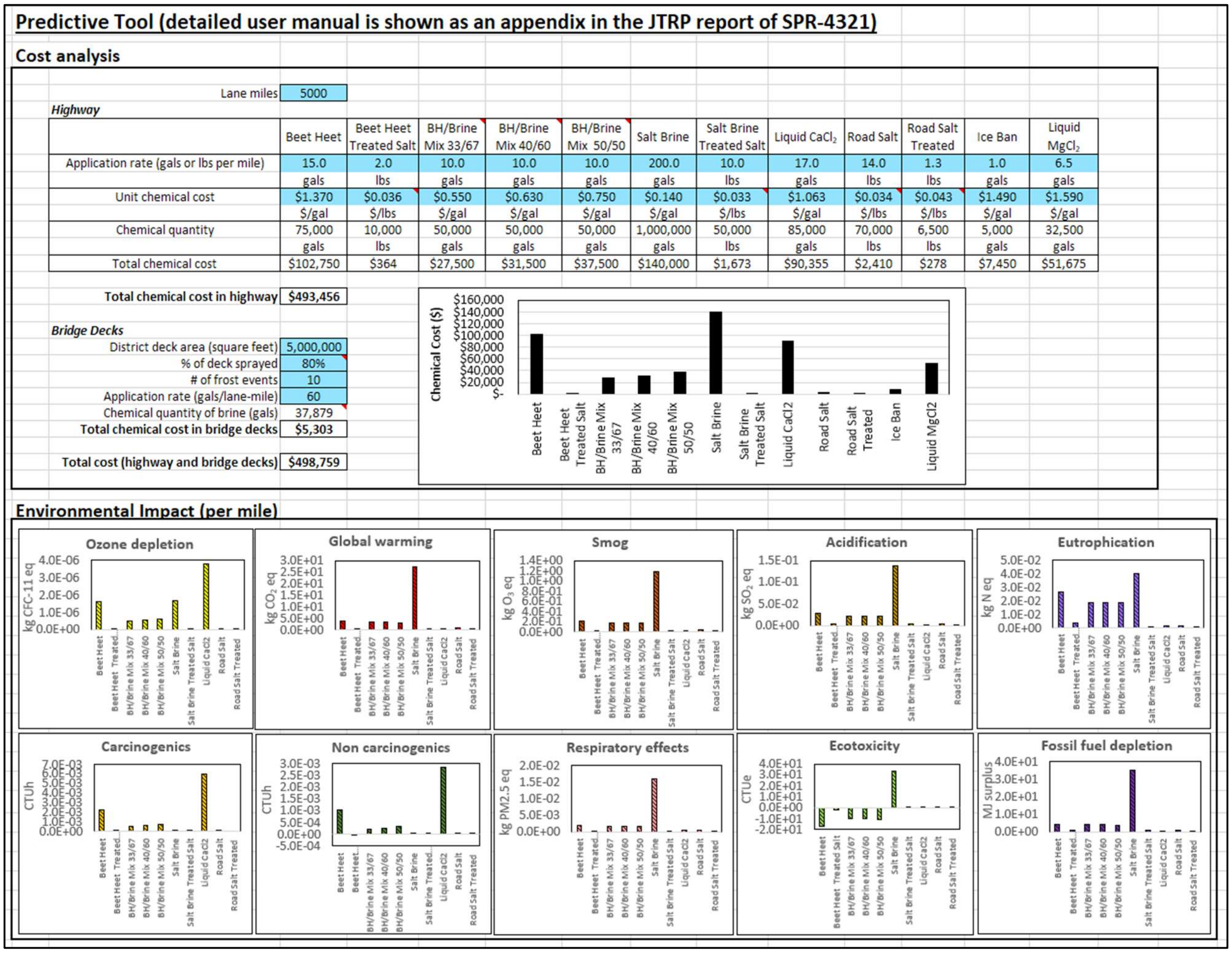
Application rate (dry salt kg) and impact of each chemical per mile

	Product Name	Beet Heet	Beet Heet Treated	BH/Brine Mix 33/67	BH/Brine Mix 40/60	BH/Brine Mix 50/50	Salt Brine	Salt Brine Treated	Liquid $CaCl_2$	Road Salt	Road Salt Treated	Ice Ban	Liquid $MgCl_2$
	Application rate (kg or lbs/lane-mile)						97.9		7.2	11.9	1.2		6.5
		gals	lbs	gals	gals	gals	gals	lbs	gals	lbs	lbs	gals	gals
$CaCl_2$	Weight (lbs/gals)	10.8	10.8	10.8	10.8	10.8			11				
	Percent of composition	13.0%	13.0%	13.0%	13.0%	13.0%			30.0%				
	Dry salt application rate (kg/lane-mile)								10.7				
	Composition in mixture	100%	0.35%	33%	40%	50%			100%				
	Dry salt application rate (kg/lane-mile)								**10.7**				
Beet juice	Weight (lbs/gals)	10.8	10.8	10.8	10.8	10.8							
	Percent of composition	15.0%	15.0%	15.0%	15.0%	15.0%							
	Dry salt application rate (kg/lane-mile)												
	Composition in mixture	100%	0.40%	33%	40%	50%							
	Dry salt application rate (kg/lane-mile)												
NaCl	Weight (lbs/gals)			9.8	9.8	9.8	9.8						
	Percent of composition		95%	23.0%	23.0%	23.0%	23.0%	92%		95%	95%		
	Dry salt application rate (kg/lane-mile)						100.1			5.1	0.5		
	Composition in mixture		99.2%	67%	60%	50%	100%	100%		100%	100%		
	Dry salt application rate (kg/lane-mile)						**100.1**			**5.1**	**0.5**		
	$CaCl_2$								**10.7**				
	Beet juice												
	NaCl						**100.1**			**5.1**	**0.5**		
	KAc												
	CMA												
	Glycerin												

Figure A.3 Screenshot of detailed calculation of environmental impact.

The last tab in the decision support tool is a "Predictive Tool" to help winter operating managers better evaluate product costs and environmental impact to support their decisions.

Overall, the template in the "Predictive Tool" (Figure A.4) is similar to previous tabs for individual districts, but the main difference is that application rates (gals or lbs per mile) for each chemical need to be manually updated, which has been highlighted in light blue color. With unit chemical costs, chemical quantity and total chemical cost can be automatically calculated.



Predictive Tool (detailed user manual is shown as an appendix in the JTRP report of SPR-4321)

Cost analysis

Lane miles 5000

Highway

	Beet Heet	Beet Heet Treated Salt	BH/Brine Mix 33/67	BH/Brine Mix 40/60	BH/Brine Mix 50/50	Salt Brine	Salt Brine Treated Salt	Liquid $CaCl_2$	Road Salt	Road Salt Treated	Ice Ban	Liquid $MgCl_2$
Application rate (gals or lbs per mile)	15.0	2.0	10.0	10.0	10.0	200.0	10.0	17.0	14.0	1.3	1.0	6.5
	gals	lbs	gals	gals	gals	gals	lbs	gals	lbs	lbs	gals	gals
Unit chemical cost	$1.370	$0.036	$0.550	$0.630	$0.750	$0.140	$0.033	$1.063	$0.034	$0.043	$1.490	$1.590
	$/gal	$/lbs	$/gal	$/gal	$/gal	$/gal	$/lbs	$/gal	$/lbs	$/lbs	$/gal	$/gal
Chemical quantity	75,000	10,000	50,000	50,000	50,000	1,000,000	50,000	85,000	70,000	6,500	5,000	32,500
	gals	lbs	gals	gals	gals	gals	lbs	gals	lbs	lbs	gals	gals
Total chemical cost	$102,750	$364	$27,500	$31,500	$37,500	$140,000	$1,673	$90,355	$2,410	$278	$7,450	$51,675

Total chemical cost in highway **$493,456**

Bridge Decks

District deck area (square feet) 5,000,000
% of deck sprayed 80%
# of frost events 10
Application rate (gals/lane-mile) 60
Chemical quantity of brine (gals) 37,879
Total chemical cost in bridge decks **$5,303**

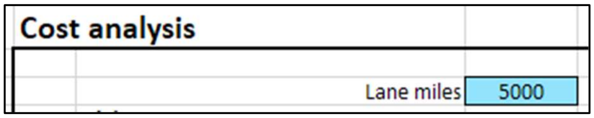
Total cost (highway and bridge decks) **$498,759**

Environmental Impact (per mile)

Figure A.4 Screenshot of cost analysis and environmental impact in the predictive tool.

A step-by-step guide of using the "Predictive Tool" is provided to demonstrate how to use the decision support tool to analyze cost and quantify environmental impact.

The first input value in the "Predictive Tool" is the total lane mile in the district and a total of 5,000 miles is assumed (Figure A.5).

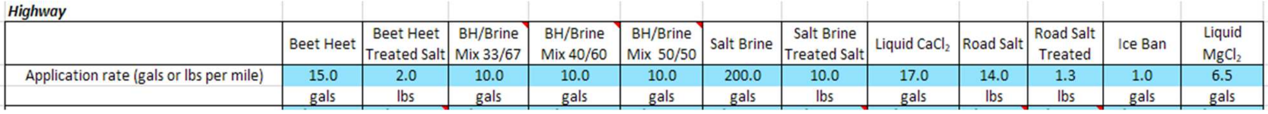


Cost analysis

Lane miles 5000

Figure A.5 Screenshot of lane mile in the predictive tool.

Then the application rate for each anti-icing and deicing chemical is estimated (Figure A.6). We used the average values of application rates from historical chemical usage data in Indiana. Other application rates can be used based on the needs and availability of anti-icing and deicing chemicals.

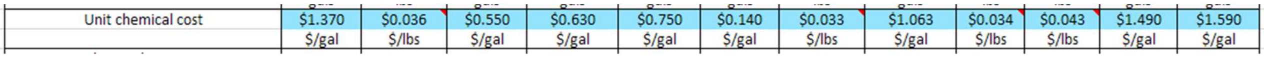


Highway

	Beet Heet	Beet Heet Treated Salt	BH/Brine Mix 33/67	BH/Brine Mix 40/60	BH/Brine Mix 50/50	Salt Brine	Salt Brine Treated Salt	Liquid $CaCl_2$	Road Salt	Road Salt Treated	Ice Ban	Liquid $MgCl_2$
Application rate (gals or lbs per mile)	15.0	2.0	10.0	10.0	10.0	200.0	10.0	17.0	14.0	1.3	1.0	6.5
	gals	lbs	gals	gals	gals	gals	lbs	gals	lbs	lbs	gals	gals

Figure A.6 Screenshot of applicate rate.

Unit chemical cost of 12 deicing chemical products are estimated based on historical data (Figure A.7).



Unit chemical cost	$1.370	$0.036	$0.550	$0.630	$0.750	$0.140	$0.033	$1.063	$0.034	$0.043	$1.490	$1.590
	$/gal	$/lbs	$/gal	$/gal	$/gal	$/gal	$/lbs	$/gal	$/lbs	$/lbs	$/gal	$/gal

Figure A.7 Screenshot of unit chemical cost in the hypothetical district.

Based on application rate and chemical unit cost, the total chemical quantity and chemical cost can be automatically calculated (Figure A.8). For example, a total of 75,000 gals of Beet Heet is needed for 5,000 miles based on an application rate of 15 gals Beer Heet per mile. Based on a unit chemical cost of $1.37/gal, the total chemical cost of Beet Heet is 75,000 gal * $1.37/gal = $102,750.

Chemical quantity	75,000	10,000	50,000	50,000	50,000	1,000,000	50,000	85,000	70,000	6,500	5,000	32,500
	gals	lbs	gals	gals	gals	gals	lbs	gals	lbs	lbs	gals	gals
Total chemical cost	$102,750	$364	$27,500	$31,500	$37,500	$140,000	$1,673	$90,355	$2,410	$278	$7,450	$51,675

Figure A.8 Screenshot of total chemical cost in the hypothetical district.

After chemical cost for each chemical is calculated, all the costs are plotted in a bar chart (Figure A.9) to give a visual presentation of the cost of applied anti-icing and deicing.

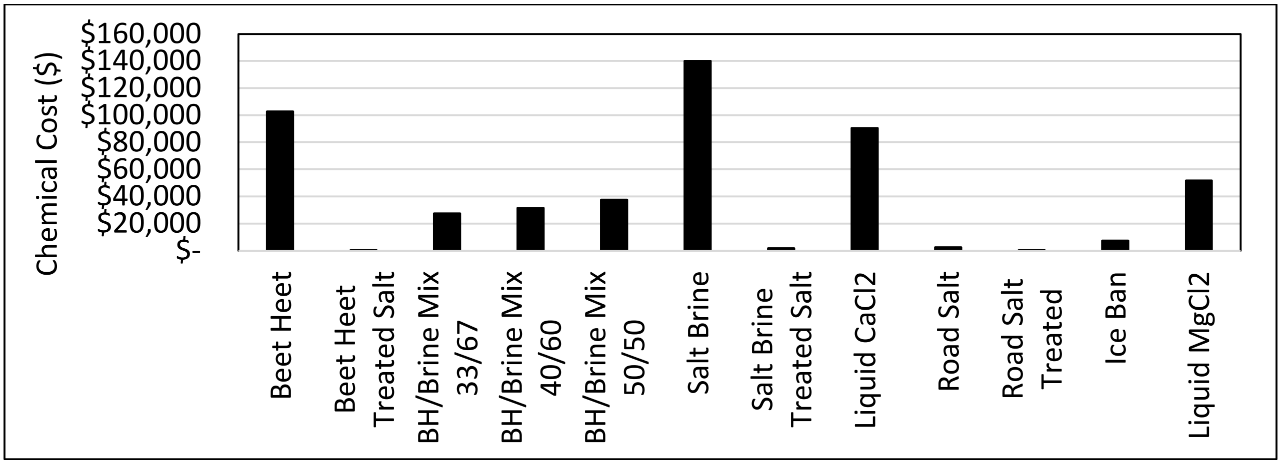


Figure A.9 Screenshot of all the chemical costs in the hypothetical district.

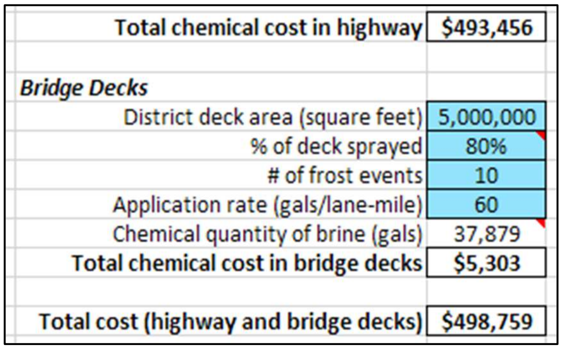
In addition to chemical costs for highway application, chemical costs in bridge decks are also calculated. A total of 5,000,000 square feet of deck area is assumed. As not all deck areas need to be sprayed, 80% deck area is assumed to be sprayed. Brine is assumed to be used to be sprayed on bridge decks. Additional assumptions include lane width of 12 feet, 10 frost events, and an application rate of 60 gals brine per mile.

The total needed chemical quantify of brine is calculated as follows:
5,000,000 feet^2 * 80%/(5,280 feet/mile * 12 feet) * 10 * 60 gals/mile = 37,879 gals

The total chemical cost in bridge decks is calculated with a unit chemical cost of $0.14/gal:
37,879 gals * $0.14/gal = $5,303

The total chemical cost for both highway and bridge decks can be calculated as follows:
$493,456 + $5,303 = $498,759.

The detailed cost analysis of bridge decks and total cost of highway and bridge decks are shown in Figure A.10.



Total chemical cost in highway	**$493,456**
Bridge Decks	
District deck area (square feet)	5,000,000
% of deck sprayed	80%
# of frost events	10
Application rate (gals/lane-mile)	60
Chemical quantity of brine (gals)	37,879
Total chemical cost in bridge decks	**$5,303**
Total cost (highway and bridge decks)	**$498,759**

Figure A.10 Screenshot of cost in bridge decks and total cost in the hypothetical district.

Subsequently, environmental impacts are automatically calculated based on the application rates of anti-icing and deicing chemicals. The specific environmental impacts include ozone depletion (Figure A.11), global warming (Figure A.12), smog (Figure A.13), acidification (Figure A.14), eutrophication (Figure A.15), carcinogenics (Figure A.16), noncarcinogenics (Figure A.17), respiratory effects (Figure A.18), ecotoxicity (Figure A.19), fossil fuel depletion (Figure A.20).

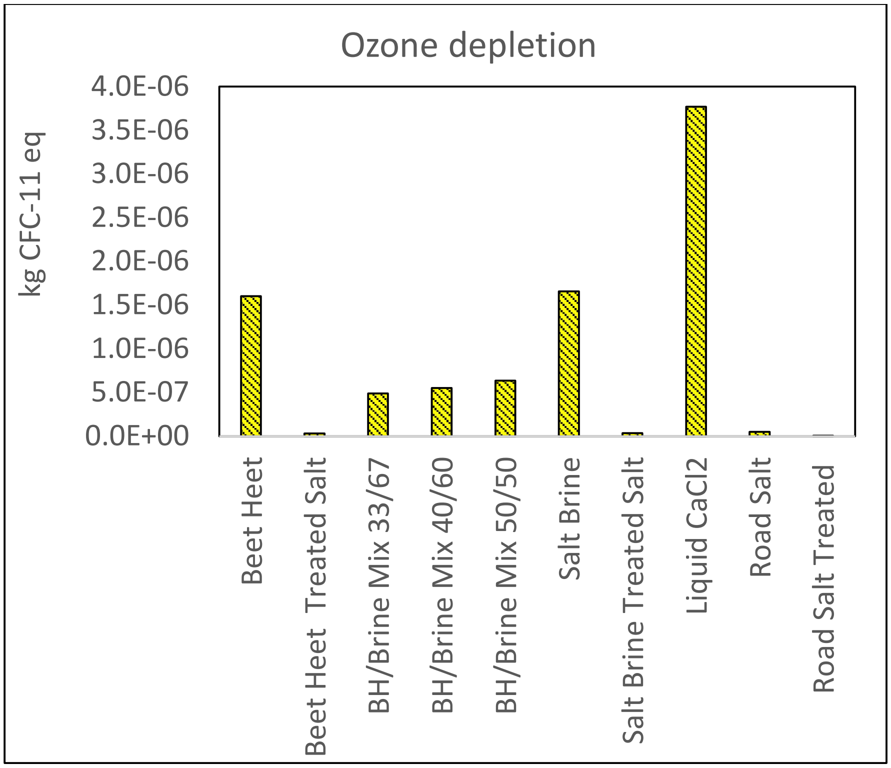


Figure A.11 Screenshot of environmental impact on ozone depletion.

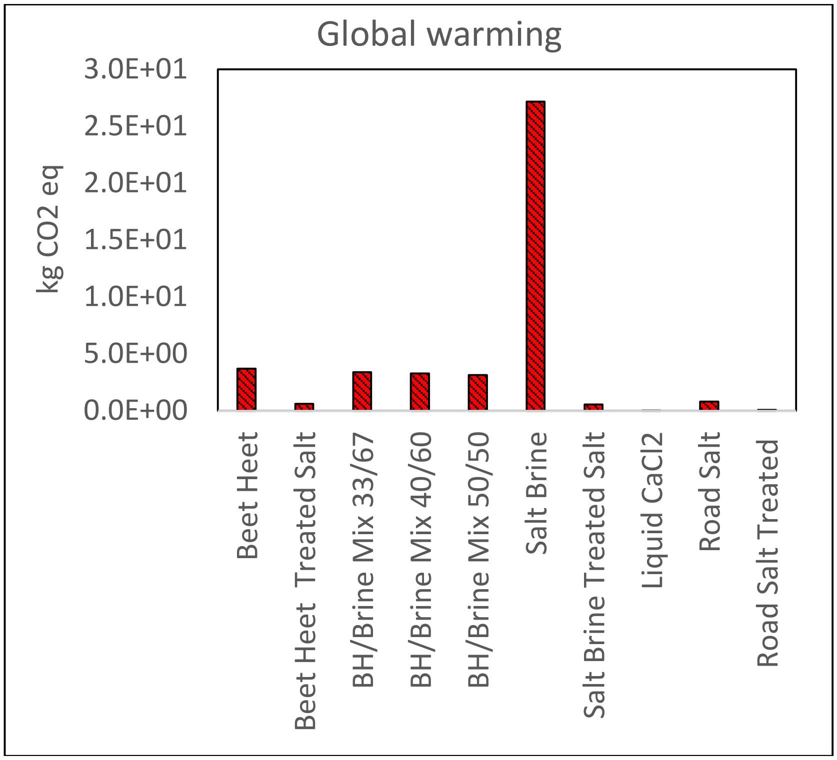


Figure A.12 Screenshot of environmental impact on global warming.

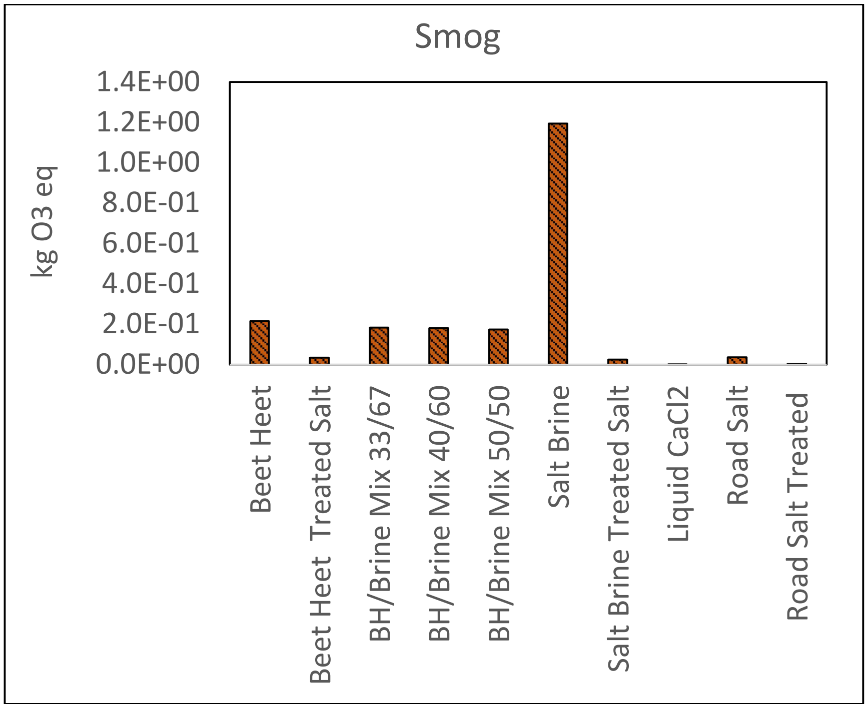


Figure A.13 Screenshot of environmental impact on smog.

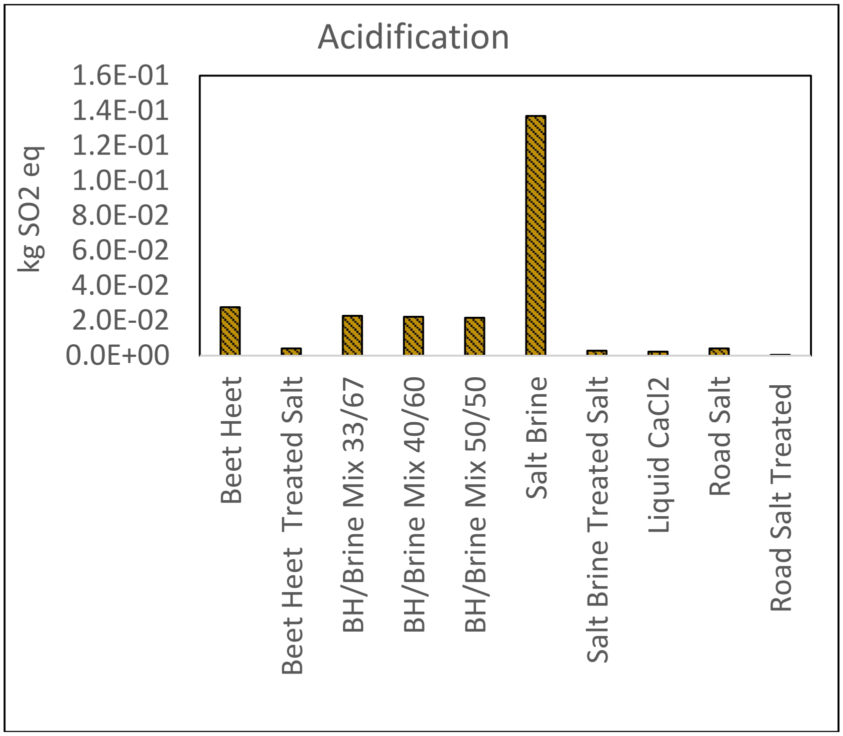


Figure A.14 Screenshot of environmental impact on acidification.

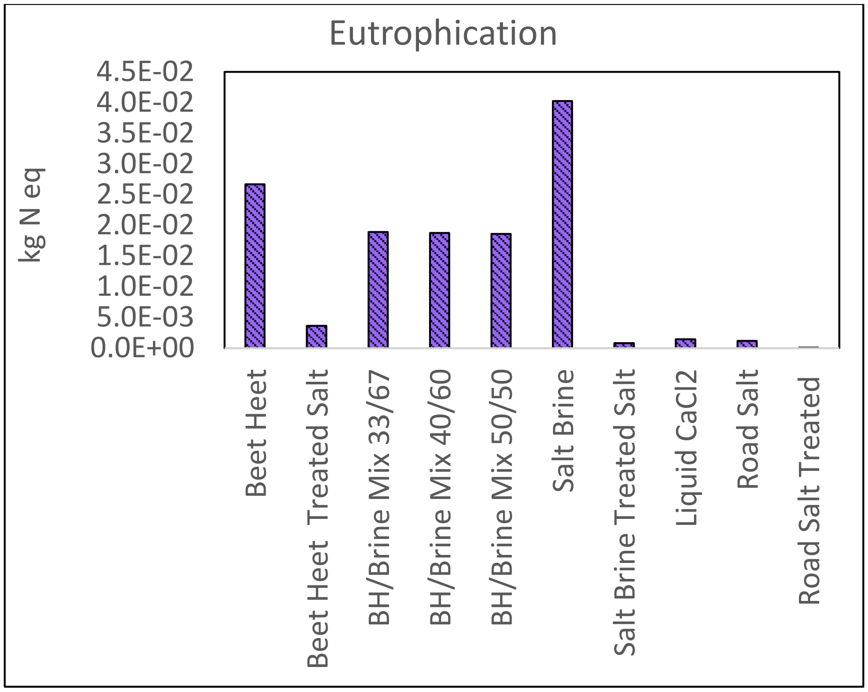


Figure A.15 Screenshot of environmental impact on acidification.

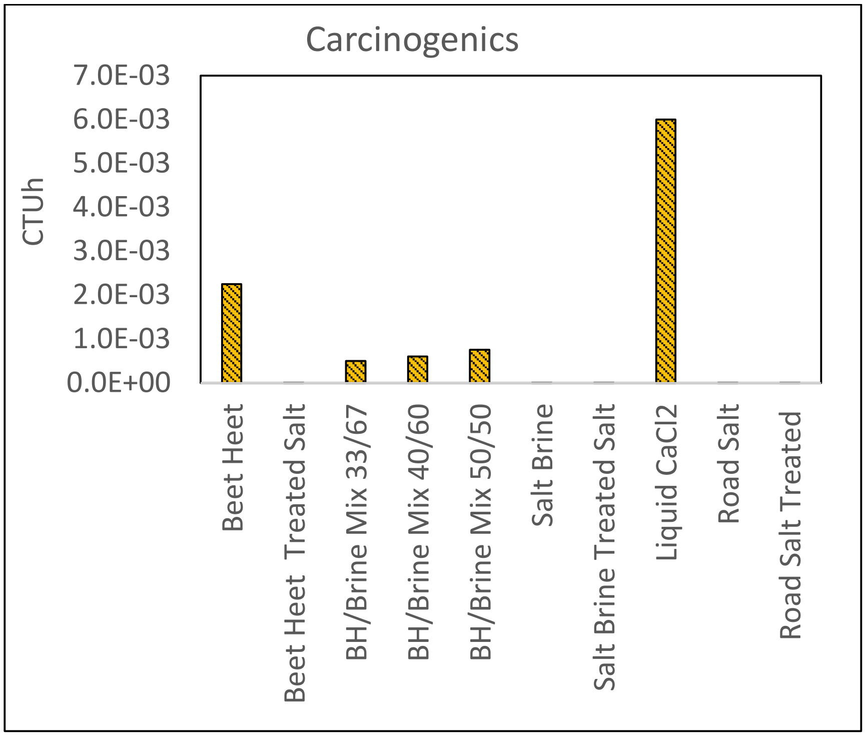


Figure A.16 Screenshot of environmental impact on carcinogenics.

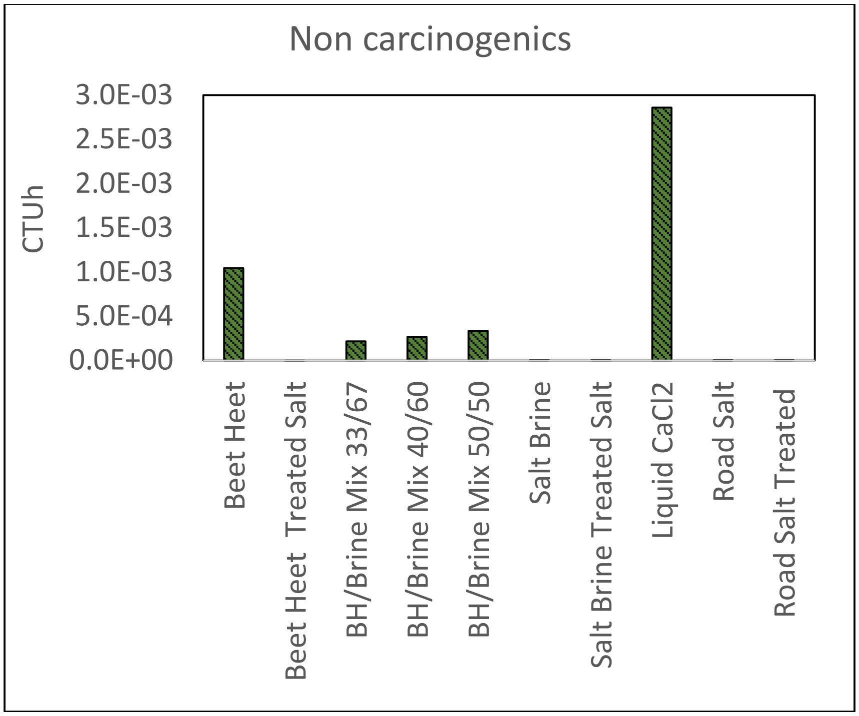


Figure A.17 Screenshot of environmental impact on noncarcinogenics.

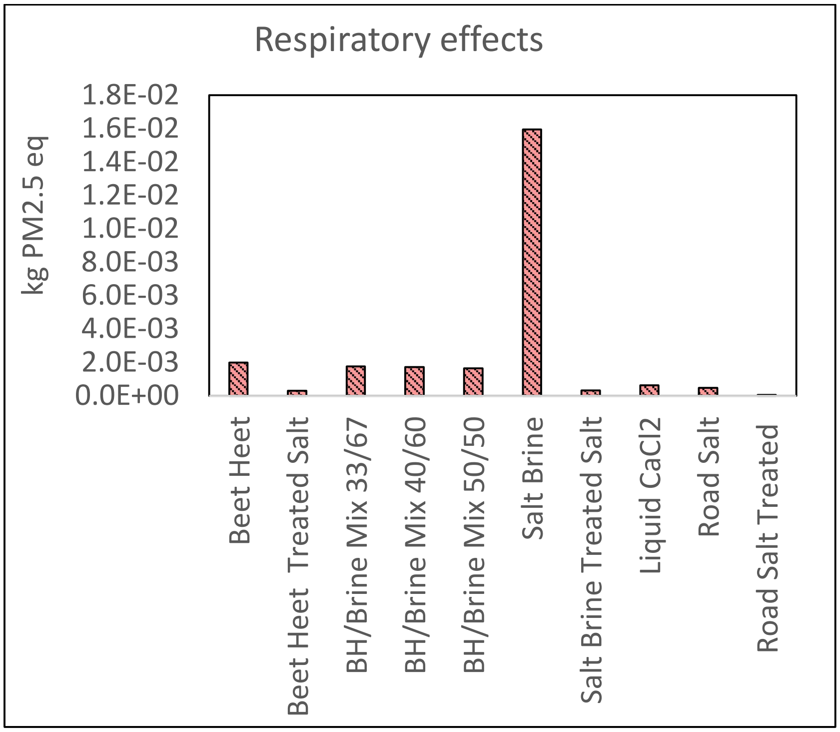


Figure A.18 Screenshot of environmental impact on respiratory effects.

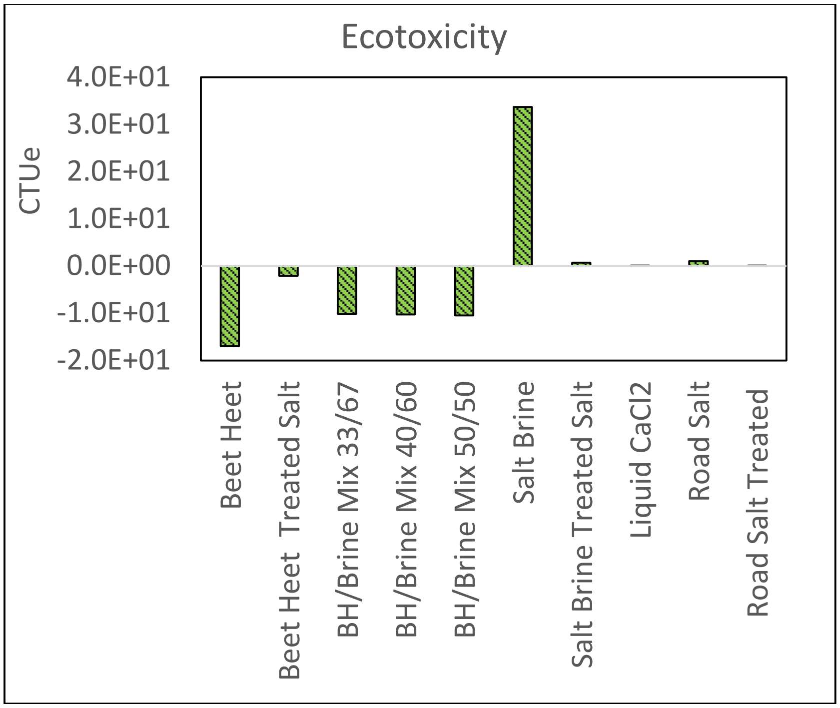


Figure A.19 Screenshot of environmental impact on ecotoxicity.

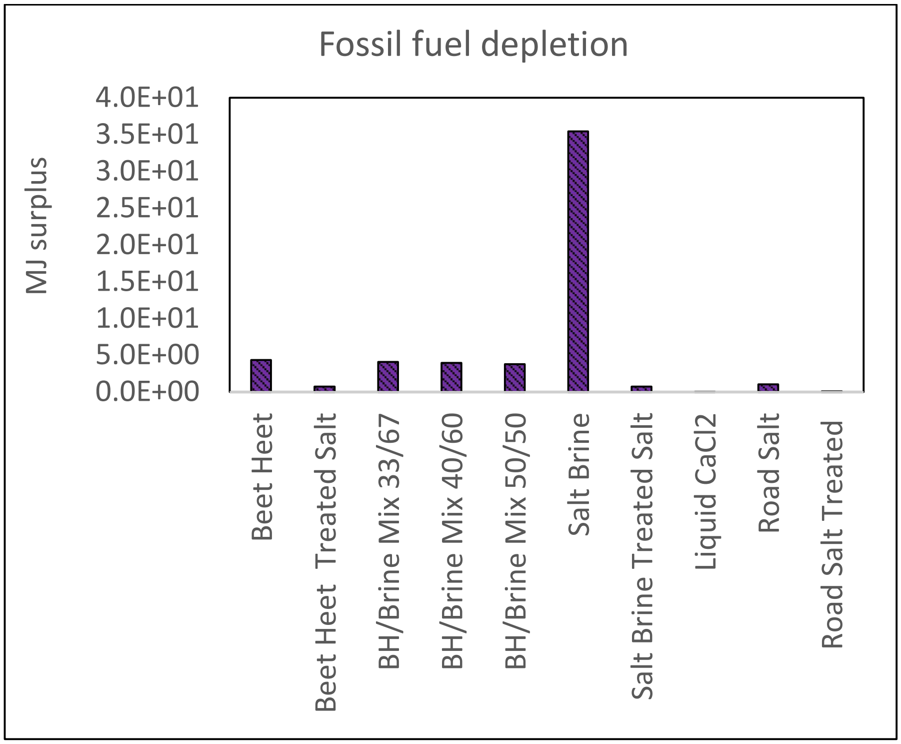
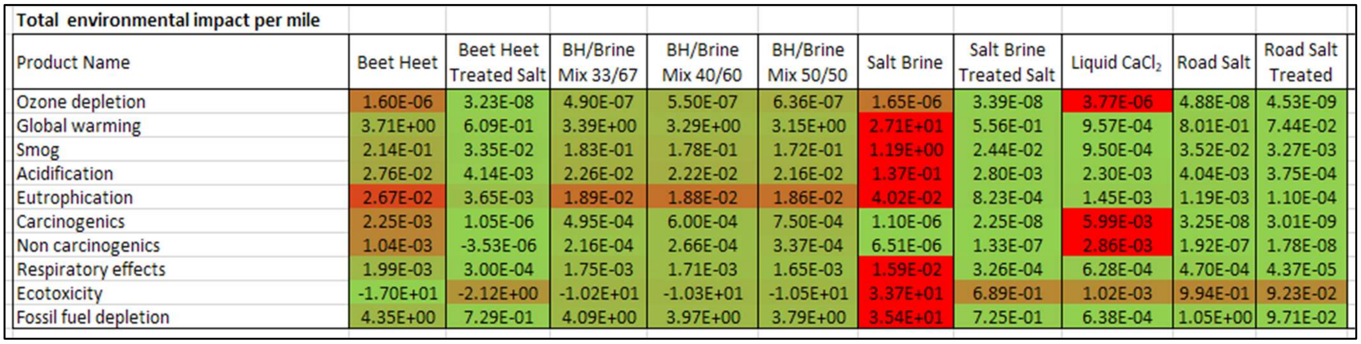


Figure A.20 Screenshot of environmental impact on fossil fuel depletion.

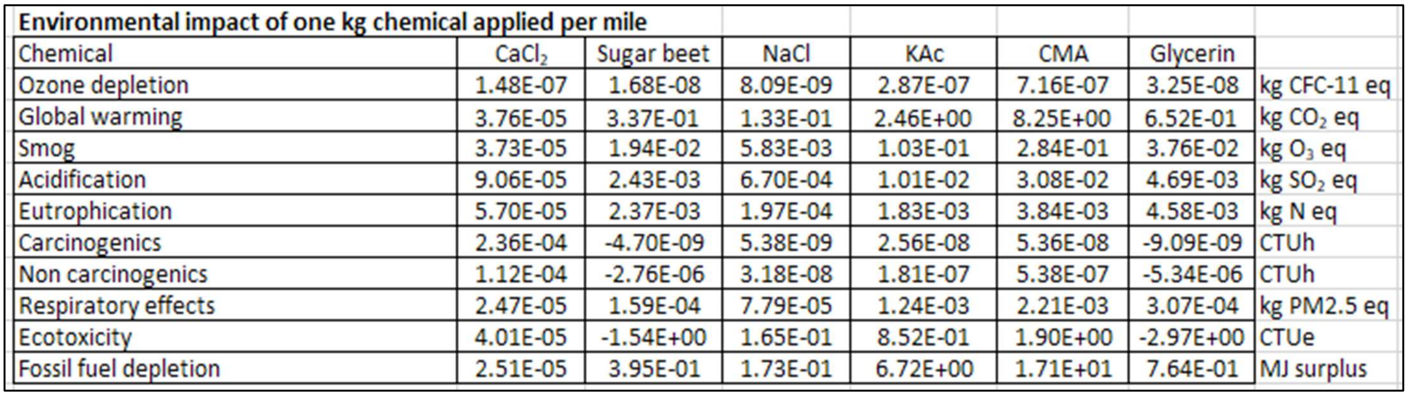
The total environmental impact per mile of all the chemicals (Figure A.21) is calculated based on environmental impact of one kg chemical applied per mile (Figure A.22) and application rate (dry salt kg) and impact of each chemical per mile (Figure A.23). For each environmental impact, the minimum environmental impact is highlighted in light green color and the maximum environmental impact is highlighted in red color.



Total environmental impact per mile

Product Name	Beet Heet	Beet Heet Treated Salt	BH/Brine Mix 33/67	BH/Brine Mix 40/60	BH/Brine Mix 50/50	Salt Brine	Salt Brine Treated Salt	Liquid $CaCl_2$	Road Salt	Road Salt Treated
Ozone depletion	1.60E-06	3.23E-08	4.90E-07	5.50E-07	6.36E-07	1.65E-06	3.39E-08	3.77E-06	4.88E-08	4.53E-09
Global warming	3.71E+00	6.09E-01	3.39E+00	3.29E+00	3.15E+00	2.71E+01	5.56E-01	9.57E-04	8.01E-01	7.44E-02
Smog	2.14E-01	3.35E-02	1.83E-01	1.78E-01	1.72E-01	1.19E+00	2.44E-02	9.50E-04	3.52E-02	3.27E-03
Acidification	2.76E-02	4.14E-03	2.26E-02	2.22E-02	2.16E-02	1.37E-01	2.80E-03	2.30E-03	4.04E-03	3.75E-04
Eutrophication	2.67E-02	3.65E-03	1.89E-02	1.88E-02	1.86E-02	4.02E-02	8.23E-04	1.45E-03	1.19E-03	1.10E-04
Carcinogenics	2.25E-03	1.05E-06	4.95E-04	6.00E-04	7.50E-04	1.10E-06	2.25E-08	5.99E-03	3.25E-08	3.01E-09
Non carcinogenics	1.04E-03	-3.53E-06	2.16E-04	2.66E-04	3.37E-04	6.51E-06	1.33E-07	2.86E-03	1.92E-07	1.78E-08
Respiratory effects	1.99E-03	3.00E-04	1.75E-03	1.71E-03	1.65E-03	1.59E-02	3.26E-04	6.28E-04	4.70E-04	4.37E-05
Ecotoxicity	-1.70E+01	-2.12E+00	-1.02E+01	-1.03E+01	-1.05E+01	3.37E+01	6.89E-01	1.02E-03	9.94E-01	9.23E-02
Fossil fuel depletion	4.35E+00	7.29E-01	4.09E+00	3.97E+00	3.79E+00	3.54E+01	7.25E-01	6.38E-04	1.05E+00	9.71E-02

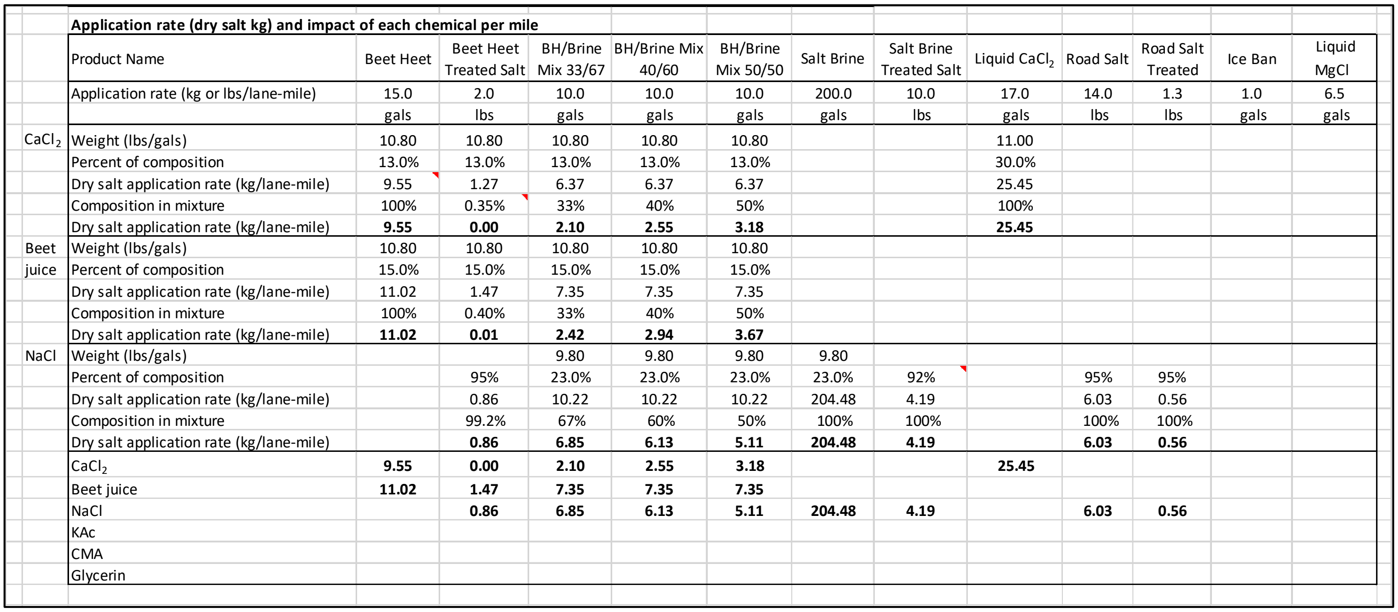
Figure A.21 Screenshot of total environmental impact per mile.



Environmental impact of one kg chemical applied per mile

Chemical	$CaCl_2$	Sugar beet	NaCl	KAc	CMA	Glycerin	
Ozone depletion	1.48E-07	1.68E-08	8.09E-09	2.87E-07	7.16E-07	3.25E-08	kg CFC-11 eq
Global warming	3.76E-05	3.37E-01	1.33E-01	2.46E+00	8.25E+00	6.52E-01	kg CO_2 eq
Smog	3.73E-05	1.94E-02	5.83E-03	1.03E-01	2.84E-01	3.76E-02	kg O_3 eq
Acidification	9.06E-05	2.43E-03	6.70E-04	1.01E-02	3.08E-02	4.69E-03	kg SO_2 eq
Eutrophication	5.70E-05	2.37E-03	1.97E-04	1.83E-03	3.84E-03	4.58E-03	kg N eq
Carcinogenics	2.36E-04	-4.70E-09	5.38E-09	2.56E-08	5.36E-08	-9.09E-09	CTUh
Non carcinogenics	1.12E-04	-2.76E-06	3.18E-08	1.81E-07	5.38E-07	-5.34E-06	CTUh
Respiratory effects	2.47E-05	1.59E-04	7.79E-05	1.24E-03	2.21E-03	3.07E-04	kg PM2.5 eq
Ecotoxicity	4.01E-05	-1.54E+00	1.65E-01	8.52E-01	1.90E+00	-2.97E+00	CTUe
Fossil fuel depletion	2.51E-05	3.95E-01	1.73E-01	6.72E+00	1.71E+01	7.64E-01	MJ surplus

Figure A.22 Screenshot of environmental impact of one kg chemical applied per mile.



Application rate (dry salt kg) and impact of each chemical per mile

	Product Name	Beet Heet	Beet Heet Treated Salt	BH/Brine Mix 33/67	BH/Brine Mix 40/60	BH/Brine Mix 50/50	Salt Brine	Salt Brine Treated Salt	Liquid $CaCl_2$	Road Salt	Road Salt Treated	Ice Ban	Liquid MgCl
	Application rate (kg or lbs/lane-mile)	15.0	2.0	10.0	10.0	10.0	200.0	10.0	17.0	14.0	1.3	1.0	6.5
		gals	lbs	gals	gals	gals	gals	lbs	gals	lbs	lbs	gals	gals
$CaCl_2$	Weight (lbs/gals)	10.80	10.80	10.80	10.80	10.80			11.00				
	Percent of composition	13.0%	13.0%	13.0%	13.0%	13.0%			30.0%				
	Dry salt application rate (kg/lane-mile)	9.55	1.27	6.37	6.37	6.37			25.45				
	Composition in mixture	100%	0.35%	33%	40%	50%			100%				
	Dry salt application rate (kg/lane-mile)	**9.55**	**0.00**	**2.10**	**2.55**	**3.18**			**25.45**				
Beet juice	Weight (lbs/gals)	10.80	10.80	10.80	10.80	10.80							
	Percent of composition	15.0%	15.0%	15.0%	15.0%	15.0%							
	Dry salt application rate (kg/lane-mile)	11.02	1.47	7.35	7.35	7.35							
	Composition in mixture	100%	0.40%	33%	40%	50%							
	Dry salt application rate (kg/lane-mile)	**11.02**	**0.01**	**2.42**	**2.94**	**3.67**							
NaCl	Weight (lbs/gals)			9.80	9.80	9.80	9.80						
	Percent of composition		95%	23.0%	23.0%	23.0%	23.0%	92%		95%	95%		
	Dry salt application rate (kg/lane-mile)		0.86	10.22	10.22	10.22	204.48	4.19		6.03	0.56		
	Composition in mixture		99.2%	67%	60%	50%	100%	100%		100%	100%		
	Dry salt application rate (kg/lane-mile)		**0.86**	**6.85**	**6.13**	**5.11**	**204.48**	**4.19**		**6.03**	**0.56**		
	$CaCl_2$	**9.55**	**0.00**	**2.10**	**2.55**	**3.18**			**25.45**				
	Beet juice	**11.02**	**1.47**	**7.35**	**7.35**	**7.35**							
	NaCl		**0.86**	**6.85**	**6.13**	**5.11**	**204.48**	**4.19**		**6.03**	**0.56**		
	KAc												
	CMA												
	Glycerin												

Figure A.23 Screenshot of application rate (dry salt kg) and impact of each chemical per mile.

We can use Beet Heet as an example to show the calculation process of environmental impact. As shown in Figure A.24, the application rate of Beet Heet is 15 gals/mile. Two components are included in Beet Heet: $CaCl_2$ and beet juice.

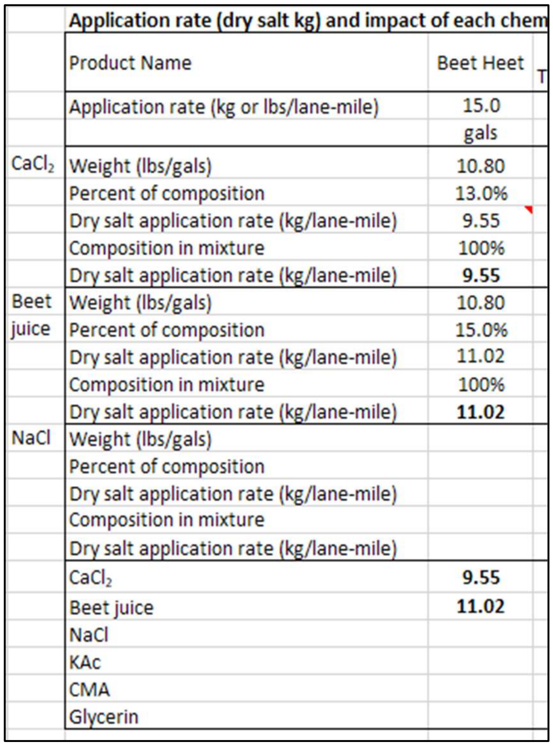
The weight of one gallon $CaCl_2$ is 10.8 lbs, and the percent of composition of $CaCl_2$ is 13%. Therefore, the dry salt application rate of $CaCl_2$ is calculated as 15 lbs/mile * 10.8 lbs/gal/2.2046 lbs/kg *13% = 9.6 kg/mile. As $CaCl_2$ is not mixed with other chemicals, the dry salt application rate is kept at 9.6 kg/mile.

In addition, the percent of composition of beet juice in Beet Heet is about 15%, and similarly, the dry salt application rate of beet juice is calculated as 15 gals/mile * 10.8 lbs/gal/2.2046 lbs/kg *15% = 11 kg/mile. NaCl, KAc, CMA, and glycerin are not included in Beet Heet and therefore the dry salt application rate is kept at 11 kg/mile.

For the environmental impact of Beet Heet on ozone depletion (Figure A.25), the application rate (Figure A.26) the contribution of each of the six compounds ($CaCl_2$, sugar beet, NaCl, KAc, CMA, glycerin) (Figure A.27) are calculated as follows:

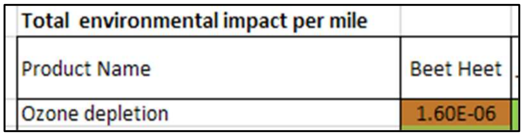
9.55 kg/mile * 1.48 * 10^{-7} $CaCl_2$ + 11.02 kg/mile * 1.68 * 10^{-8} sugar beet + 0 kg/mile * 8.09 * 10^{-9} NaCl + 0 kg/mile * 2.87 * 10^{-7} KAc + 0 kg/mile * 7.16 * 10^{-7} CMA +0 kg/mile * 3.25 * 10^{-8} glycerin = 1.60 * 10^{-6} kg CFC-11 eq

Environmental impact on other categories can be calculated similarly. If a new anti-icing or deicing chemical is used, their environmental chemical can be calculated using the procedure described above if chemical compositions are known.



	Application rate (dry salt kg) and impact of each chem	
	Product Name	Beet Heet
	Application rate (kg or lbs/lane-mile)	15.0 gals
$CaCl_2$	Weight (lbs/gals)	10.80
	Percent of composition	13.0%
	Dry salt application rate (kg/lane-mile)	9.55
	Composition in mixture	100%
	Dry salt application rate (kg/lane-mile)	**9.55**
Beet juice	Weight (lbs/gals)	10.80
	Percent of composition	15.0%
	Dry salt application rate (kg/lane-mile)	11.02
	Composition in mixture	100%
	Dry salt application rate (kg/lane-mile)	**11.02**
NaCl	Weight (lbs/gals)	
	Percent of composition	
	Dry salt application rate (kg/lane-mile)	
	Composition in mixture	
	Dry salt application rate (kg/lane-mile)	
	$CaCl_2$	**9.55**
	Beet juice	**11.02**
	NaCl	
	KAc	
	CMA	
	Glycerin	

Figure A.24 Screenshot of application rate (dry salt kg) and impact of Beet Heet in the hypothetical district.

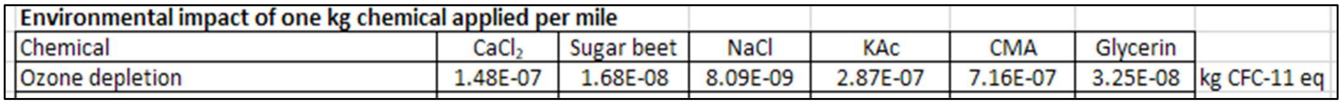


Total environmental impact per mile	
Product Name	Beet Heet
Ozone depletion	1.60E-06

Figure A.25 Screenshot of application rate (dry salt kg) and impact of Beet Heet.

$CaCl_2$	**9.55**
Beet juice	**11.02**
NaCl	
KAc	
CMA	
Glycerin	

Figure A.26 Screenshot of application rate (dry salt kg) of Beet Heet per mile.



Environmental impact of one kg chemical applied per mile							
Chemical	$CaCl_2$	Sugar beet	NaCl	KAc	CMA	Glycerin	
Ozone depletion	1.48E-07	1.68E-08	8.09E-09	2.87E-07	7.16E-07	3.25E-08	kg CFC-11 eq

Figure A.27 Screenshot of environmental impact on ozone depletion of one kg chemical applied per mile.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

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