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DEICER USAGE ON CONCRETE AND ASPHALT PAVEMENTS IN UTAH

Prepared For:

Utah Department of Transportation
Research Division

Submitted By:

Brigham Young University
Department of Civil and Environmental Engineering
Engineering

Authored By:

W. Spencer Guthrie, Ph.D.
Chase D. Thomas

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16. Abstract

The objectives of this research were to 1) compile winter maintenance data for the Utah Department of Transportation (UDOT) to directly compare concrete and asphalt pavements with regards to deicer usage and 2) determine if there is a statistical difference in deicer usage on concrete and asphalt pavements. To this end, three data sources were consulted for this research: Maintenance Management Quality Assurance (MMQA) database, UDOT road database, and Google Maps. The final compiled data set prepared for analysis in this research contained deicer quantities by deicer type, pavement surface areas by pavement material type, traffic, longitude, latitude, and elevation data. The deicer data evaluated in this analysis represented the total quantities of each deicer distributed during the 8-year period during which the MMQA database was used by UDOT.

Several multiple linear regression analyses were performed to determine if concrete or asphalt pavements required different amounts of deicers, including salt, Redmond salt, brine, wetted salt, magnesium chloride, sand, pre-mix, and wetted pre-mix, during the winter seasons evaluated in this research. From the results of the statistical analyses, concrete proportion was statistically significant in models for three of the dependent variables, including brine, wetted salt, and wetted pre-mix. However, neither the full nor the reduced regression model prepared for the sum of all deicers had concrete proportion as one of the significant variables. The absence of concrete proportion as an independent variable in these models shows that, on average, after correcting for differences in traffic volume and pavement area, deicer usage in Utah is not affected by pavement type. Therefore, except in areas where applications of brine, wetted salt, and wetted pre-mix are common, winter maintenance costs should not be a factor in the determination of pavement type.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

AADT	annual average daily traffic
CSH	calcium-silicate-hydrate
DOTs	departments of transportation
FHWA	Federal Highway Administration
MMQA	Maintenance Management Quality Assurance
MSH	magnesium-silicate-hydrate
OLS	ordinary least squares
SQL	Structured Query Language
UDOT	Utah Department of Transportation

EXECUTIVE SUMMARY

The objectives of this research were to 1) compile winter maintenance data for the Utah Department of Transportation (UDOT) to directly compare concrete and asphalt pavements with regards to deicer usage and 2) determine if there is a statistical difference in deicer usage on concrete and asphalt pavements. To this end, three data sources were consulted for this research: Maintenance Management Quality Assurance (MMQA) database, UDOT road database, and Google Maps. The final compiled data set prepared for analysis in this research contained deicer quantities by deicer type, pavement surface areas by pavement material type, traffic, longitude, latitude, and elevation data. The deicer data evaluated in this analysis represented the total quantities of each deicer distributed during the 8-year period during which the MMQA database was used by UDOT.

Several multiple linear regression analyses were performed to determine if concrete or asphalt pavements required different amounts of deicers, including salt, Redmond salt, brine, wetted salt, magnesium chloride, sand, pre-mix, and wetted pre-mix, during the winter seasons evaluated in this research. Because plow routes were not equal in total pavement area, a variable called “concrete proportion” was created. Similarly, traffic and deicer quantities were divided by total pavement area in lane miles to account for the variation in maintenance station sizes and to allow for direct comparison of the various maintenance stations. After the values of the independent variables were finalized, full and reduced models were created for the total amount of all deicers per lane mile and the amounts of each of the eight individual deicers per lane mile based on the statistical significance of the respective independent variables. A total of 18 regression models were completed for this research.

From the results of the statistical analyses, concrete proportion was statistically significant in models for three of the dependent variables, including brine, wetted salt, and wetted pre-mix. However, neither the full nor the reduced regression model prepared for the sum of all deicers had concrete proportion as one of the significant variables. The absence of concrete proportion as an independent variable in these models shows that, on average, after correcting for differences in traffic volume and pavement area, deicer usage in Utah is not affected by pavement type. Therefore, except in areas where applications of brine, wetted salt,

and wetted pre-mix are common, winter maintenance costs should not be a factor in the determination of pavement type.

1.0 INTRODUCTION

1.1 Problem Statement

Each winter, roadway managers in cold regions strive to direct funds for snow and ice removal in the most efficient ways possible. The plowing and deicing of roads is both costly and time-consuming, requiring rapid responses to sudden changes in road safety due to snow and ice accumulation. On average, state departments of transportation (DOTs) spend 20 percent of their budget on winter maintenance activities (*1*). According to the Federal Highway Administration (FHWA), the Utah Department of Transportation (UDOT) spent $22 million on snow and ice removal in 2009 (*1*).

The UDOT highway network consists of both concrete and asphalt pavements. The selection of pavement type depends on several factors, including initial construction cost, traffic loads, and long-term maintenance. UDOT engineers currently prefer concrete pavement in high-traffic areas because it requires less maintenance and provides longer service life relative to asphalt pavement. However, asphalt roads are more common throughout Utah due to ease of placement and low initial costs relative to concrete roads.

In the past, winter maintenance costs have not been a factor in the determination of pavement type. However, with rising winter maintenance costs, as shown in Figure 1.1, UDOT engineers are interested in determining whether concrete or asphalt roads require greater deicer quantities to maintain safe traveling conditions during winter months (*1*). This information would allow UDOT and other DOTs in cold regions to make better decisions regarding pavement type selection in areas that require snow and ice removal.

Past research on pavement materials and winter maintenance has typically been related to deleterious effects of deicers, pavement life-cycle costs, and general winter maintenance practices (*2, 3, 4, 5, 6, 7, 8, 9, 10, 11*). Although these studies are important to DOTs in cold regions, none of the documents identified in the literature review performed in this research quantitatively compare deicer usage for concrete and asphalt pavements. One study, which was related to pavement life-cycle costs, included winter maintenance costs, but detailed information related to deicer types and quantities was not included (*4*).

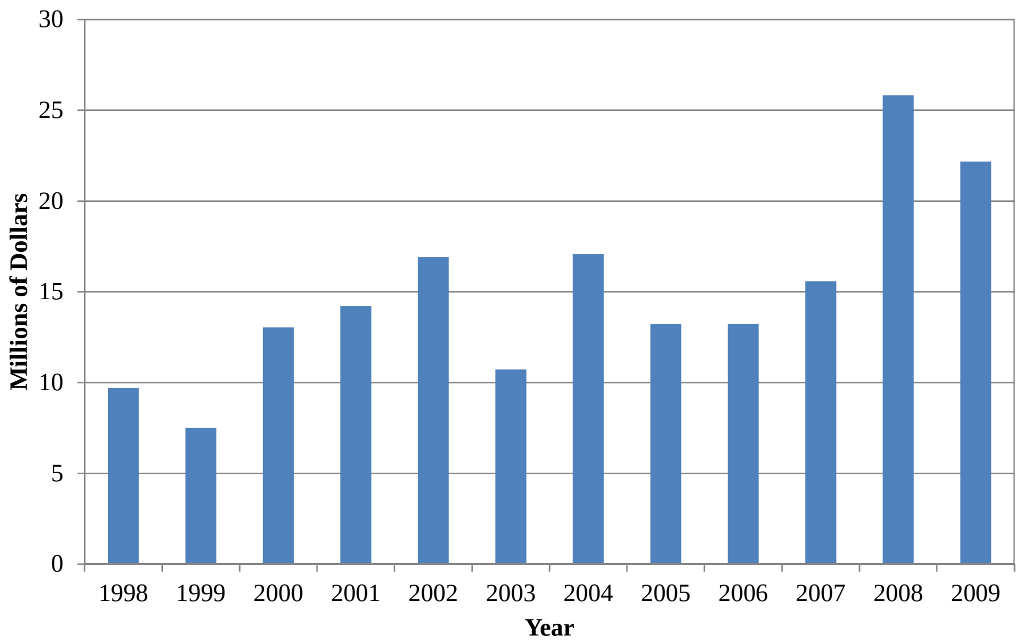

Figure 1.1 Yearly snow and ice removal costs for UDOT.

1.2 Research Objectives and Scope

The objectives of this research were to 1) compile UDOT's winter maintenance data to directly compare concrete and asphalt pavements with regards to deicer usage and 2) determine if there is a statistical difference in deicer usage on concrete and asphalt pavements. The results of this research will supplement information currently used by pavement engineers in the selection of pavement type.

The research conducted in this study specifically compared the deicer usage on concrete and asphalt pavements within the jurisdiction of UDOT from the years 2002 to 2009. UDOT personnel provided data tables that included the following information: plow routes, types and quantities of deicers placed on each plow route, traffic loads, pavement types, and pavement areas. Latitude and elevation were determined for each UDOT winter maintenance station using Google Maps data. Software was developed to compile all of the data and prepare it for statistical analysis. Multiple linear regression models were created to determine if there was a statistical difference between deicer usage on concrete and asphalt pavements in Utah.

1.3 Outline of Report

This report contains five chapters. Chapter 1 includes the problem statement, objectives, and scope of this research. Chapter 2 presents background information on UDOT's winter maintenance operations and deicers. Chapter 3 describes the data sources, data compilation procedures, and statistical analyses. Chapter 4 reports the results of the data compilation and statistical analysis and provides a discussion of the research findings. Chapter 5 provides a summary of the research, findings, and recommendations.

2.0 BACKGROUND

2.1 Overview

The following sections present findings from a literature review focused on UDOT's winter maintenance operations. Information regarding deicers is also provided.

2.2 Winter Maintenance Operations

The primary goal of any winter maintenance operation is to economically provide safe and passable roads during the winter months. The following sections discuss the economics of winter maintenance programs, details on the organization of UDOT's winter maintenance operation, and technology and methods used by UDOT for snow and ice removal.

2.2.1 Economics

Because the transportation system is vital to industry and commerce, breakdowns in the transportation system due to snow and ice have adverse effects on local economies (*12*). Snowfall, for example, can reduce highway traffic speeds by up to 40 percent, which has a direct effect on the transportation of goods and services (*13*). According to FHWA, the cost of weather-related delays for trucking companies in the United States each year is $3.4 billion (*14*). The adverse economic impact of unsafe winter roads is the primary reason that winter operations exist and why agencies are constantly striving to improve their operations.

Fuel for plow trucks and large quantities of deicers required each year comprise the majority of costs for a DOT winter maintenance budget. During the 2007-2008 winter maintenance season, UDOT's costs were $25 million (*15*). During that same season, UDOT used 3.2 million gallons of diesel fuel, which at the time cost $3.50 per gallon (*16*). Based on a 10-year average, UDOT uses 224,000 tons of sodium chloride per year, which has an average unit cost of $30 per ton (*15*, *17*). Therefore, for the 2007-2008 season, the cost of diesel fuel and sodium chloride alone totaled $18 million, which accounted for 72 percent of UDOT's winter maintenance budget.

2.2.2 UDOT's Winter Maintenance Operation

As of 2012, UDOT is responsible for maintenance of over 18,000 lane miles of roads each winter; this pavement area is equal to a five-lane highway stretching across the United States from California to Maine. UDOT's winter maintenance division has 503 full-time snow plow operators and 85 construction and seasonal employees, and it operates 498 plow trucks throughout the state. Based on data collected from the years 2002 to 2007, UDOT has plowed an estimated 65 million tons of snow annually (personal communication, L. Bernhard, Maintenance Methods Engineer, UDOT, February 26, 2013).

To facilitate the task of snow and ice removal in Utah, UDOT has divided the state into 73 maintenance stations. Each maintenance station is subdivided into plow routes. The stations vary in size and number of plow routes, depending on population density; for example, areas with high populations like Salt Lake City have large maintenance stations with many routes and plow trucks. Each maintenance station operates semi-autonomously; therefore, the winter maintenance operation in Utah is not necessarily coordinated statewide. All maintenance stations have on-site salt storage, with 55 stations using covered salt storage facilities.

2.2.3 Technology and Methods

UDOT plows state roads and spreads deicers using a dump truck fitted with plow blades. The current standard plow truck is equipped with a 7.5-cubic-yard stainless steel storage bin and spreader for deicers, a stainless steel dump body, and fiberglass fenders and body. The frame and drive train are composed of steel but are isolated from the corrosive deicers. A typical plow truck is shown in Figure 2.1 (photograph by Eric Wizke 2005). As of 2012, half of all UDOT plow trucks have wing plows (personal communication, L. Bernhard, Maintenance Methods Engineer, UDOT, August 20, 2012). A wing plow, depicted in Figure 2.2 (photograph by UDOT 2012), allows for two lanes to be plowed at the same time, doubling the turnaround rate for the plowing operation and reducing fuel costs.

Advancements in technology have allowed UDOT to decrease operating costs. As of 2012, UDOT is testing global positioning systems on 10 of their trucks (personal communication L. Bernhard, Maintenance Methods Engineer, UDOT, August 20, 2012). The program is still in

Figure 2.1 Typical UDOT plow truck.

Figure 2.2 Wing plow.

development, but UDOT hopes to further optimize winter maintenance activities by monitoring the deicer spreading rates and truck idle time, for example, and implementing improvements that decrease truck maintenance costs. In addition, UDOT has installed 52 standard weather stations to monitor weather conditions and, as of 2009, had installed 47 state-of-the-art environmental sensor stations to support the UDOT road weather information system. This system provides real-time information on road conditions and also historic data that can be processed and analyzed by UDOT engineers. The majority of the stations are equipped with cameras to also allow for remote visual inspection of a given area. The data are extremely useful to winter maintenance personnel, as specific knowledge regarding the severity of a winter storm enables application of the most appropriate treatments.

2.3 Deicers

Deicers are ionic salts that dissolve into ions when they come in contact with water. An ionic salt is composed of cations (positively charged ions) and anions (negatively charged ions). Common deicer cations are sodium and magnesium, and common deicer anions are chloride and sulfate. Because ions are charged particles, they interact electrically with water. Because the water molecule has a net negative end, resulting from the oxygen atom, and a net positive end, resulting from the hydrogen atoms, ionic compounds can be dissolved in water. Ionic compounds will dissolve in water only if the net attraction between the polar water molecules and the compound's ions is greater than the ionic bonds within the compound itself. A diagram of how an ionic salt dissolves in water is given in Figure 2.3.

Due to the colligative properties of solutions, water with any concentration of dissolved ions will have a lower freezing point than water in pure form. The magnitude of the depression in the freezing point of water is directly proportional to the amount of ions in solution and not the specific type of ion (*18*). Magnesium chloride ($MgCl_2$), for example, releases three ions per molecule dissolved in solution and would therefore depress the freezing point of water more than sodium chloride (NaCl), which releases only two ions per molecule dissolved.

Surface water exists on ice as water molecules transition between solid and liquid states; however, the relative quantity of surface water is proportional to the temperature of the ice. When deicers are introduced to ice, the dynamic equilibrium between the ice and the surface water is disrupted. Surface water, which was in equilibrium with the ice prior to application of the deicer, dissolves the deicer, and the resulting solution has a lower freezing point than pure water. The loss of surface water to dissolve the deicer causes more water molecules to transition from a solid phase to a liquid phase to re-establish equilibrium. As this process continues, the

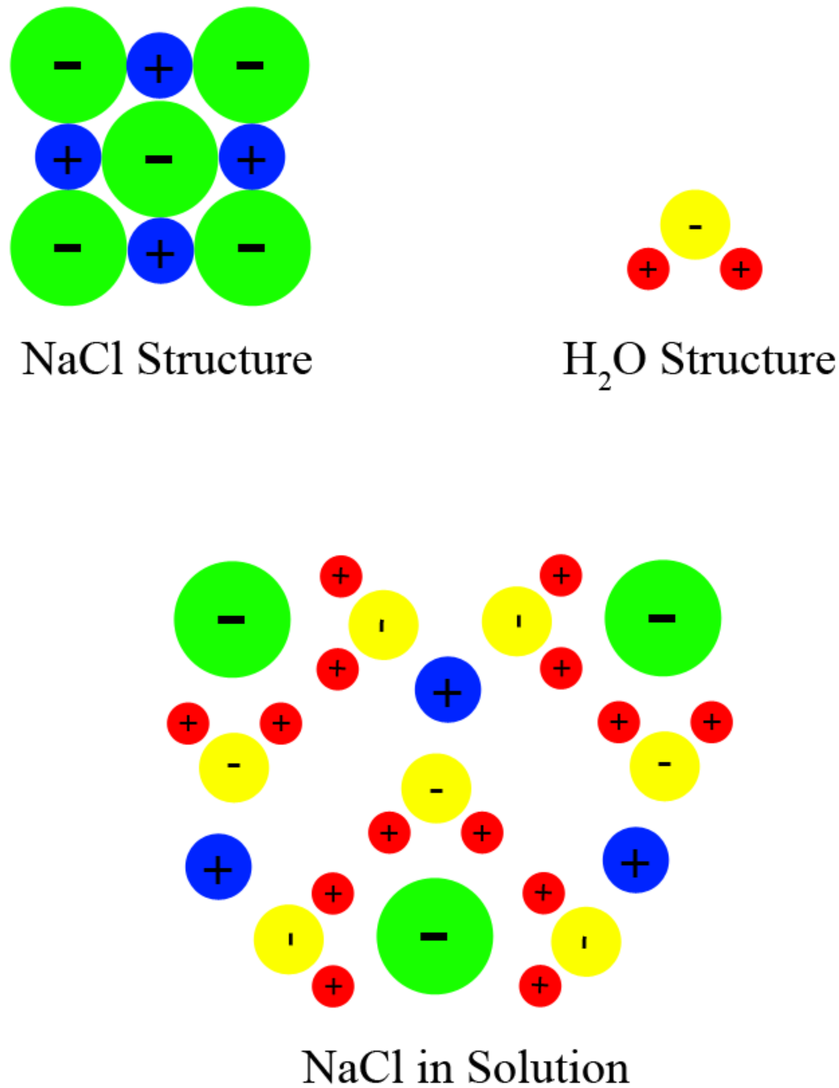

Figure 2.3 Sodium chloride and water in solution.

ice melts; however, if the temperature decreases, the amount of surface water molecules is reduced as a result of the reduction in the available energy in the system, and the chemical process then decelerates (*18*).

Because the chemical interaction between ice and deicers is temperature-related, deicers have a minimum effective temperature for snow and ice removal in the field, which is usually higher than the freezing temperature of a saturated salt solution as measured in a controlled laboratory setting. The primary reason for this difference is that, as temperature decreases, higher concentrations of deicers and longer amounts of time are required to melt snow and ice. At 30°F, for example, a given amount of sodium chloride can melt five times as much ice as it can at 20°F (*19*). During the melting process in the field, undissolved deicers can be readily removed from the pavement surface by traffic and wind, which reduces the efficiency of the deicing process. Therefore, salts that readily dissolve at the given pavement surface temperature are the best to use because they are the most likely to be retained on the pavement. Although the deicer can still lower the freezing point below the minimum effective temperature, it may not effectively break the bond between the pavement and ice before it is removed from the road.

As described in the following sections, sodium chloride, magnesium chloride, and abrasives are products commonly used by UDOT for winter maintenance. UDOT also employs mixtures of these products with each other and/or water.

2.3.1 Sodium Chloride

Sodium chloride is an ionic compound formed from sodium and chlorine. Ionic bonds between these elements form a face-centered cubic crystal lattice reflected in the shape of typical salt crystals. Figure 2.4 (*20*) depicts the structure of sodium chloride.

Sodium chloride has a maximum solubility of 26 percent by weight (2.97 lb/gal) in water at a temperature of 32°F. In a laboratory setting, sodium chloride can lower the freezing point of water to -6°F (*19*). In the field, however, the lowest effective temperature at which snow and ice can be removed using sodium chloride is approximately 15°F (personal communication, L. Bernhard, Maintenance Methods Engineer, UDOT, March 17, 2010).

The Great Salt Lake in northern Utah is the primary source of salt for UDOT, although other salt mines, such as the Redmond mine, are also used. The Great Salt Lake is the fourth largest terminal lake, or lake without outlets, in the world. Because it is terminal, the salinity of the water is about three to five times higher than that of the ocean. An estimated 2.2 million tons of salts enter the lake each year through ground water and surface entrances to the lake. The salt industries extract an estimated 2.5 million tons of salts annually. Sodium chloride comprises the majority of salts extracted, with other salts and elements including magnesium, potassium,

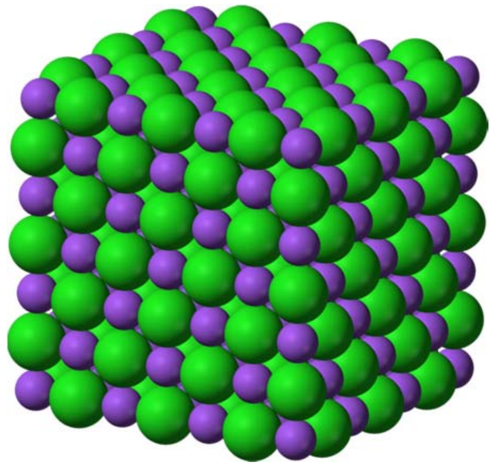

Figure 2.4 Sodium chloride crystal lattice.

sulfate, and carbonate also being extracted (*21*). Sodium chloride is extracted using a solar drying process and mined using scrapers and loaders.

The spreading rate and timing for sodium chloride vary with storm magnitude and climate, but typical spreading rates for solid sodium chloride range from 100 to 300 pounds per lane mile when applied prior to storm events (*19*). As of 2010, typical spreading rates in Utah have been 250 pounds of sodium chloride per lane mile (personal communication, L. Bernhard, Maintenance Methods Engineer, UDOT, March 17, 2010). Application of sodium chloride before storm events or when the snow is still loose is critical for efficient removal of the snow and ice from roads. Early application prevents snow and ice from bonding to the road and also promotes the creation of slush, which is desirable because it resists packing and can therefore be efficiently removed from the road surface by plow trucks (*19*).

Sodium chloride can also be applied as a brine, which is a liquid solution of any particular salt, or it can be pre-wetted with either water or liquid deicers. UDOT specifically prepares sodium chloride brine at a concentration of 23 percent dissolved sodium chloride by weight. Advantages of using brine and/or pre-wetting include faster melting action and reductions in deicer waste because of the decreased effect of either traffic or wind in removing the deicers from the pavement surface. According to one state agency, the amount of lost or wasted salt can be reduced by 20 to 30 percent through the use of brines or pre-wetted deicers (*19*).

Although sodium chloride is a naturally occurring mineral, there are detrimental effects to the environment and to pavements when it is used as a deicer on roads. Studies have shown that runoff from sodium chloride affects soil and vegetation within 60 ft of treated roads (*19*). In Wisconsin, salinity levels in surface and ground water have increased since 1960, with the increases being attributed to roadway deicing (*19*). Even though no damage to aquatic life or ecosystems has been reported, rising salinity levels are detrimental to the overall environment and should be monitored or controlled (*22*). Sodium chloride, in addition to being detrimental to the environment, is also harmful to concrete pavements and bridge decks. Specifically, sodium chloride causes scaling of concrete surfaces and increases the rate of corrosion of embedded steel reinforcement. Proper concrete mixture design and construction practices combined with proper deicer spreading rates are needed to minimize long-term damage.

2.3.2 Magnesium Chloride

Magnesium chloride is composed of magnesium and chlorine. Magnesium chloride is an ionic halide with a great affinity for water; therefore, it has several hydrate forms. The ionic bonds create a complex crystal structure with rhombohedral symmetry. Figure 2.5 (*23*) depicts the crystal structure of magnesium chloride.

Magnesium chloride is highly soluble in water in both anhydrous and hydrate forms. Magnesium chloride has a maximum solubility of 35.2 percent by weight (4.53 lb/gal) in anhydrous form and 61 percent by weight (13.1 lb/gal) in hydrate form at room temperature. As previously described, magnesium chloride causes a greater freezing point depression than sodium chloride. In a laboratory environment, a saturated solution of magnesium chloride will have a freezing temperature of approximately -25°F, although the lowest effective temperature for magnesium chloride when used as a deicer in the field is approximately -5°F. Because magnesium chloride has higher solubility and a lower effective deicing temperature than sodium chloride, it is an excellent choice for anti-icing applications (personal communication, L. Bernhard, Maintenance Methods Engineer, UDOT, March 17, 2010).

As with sodium chloride, the primary source of magnesium chloride for UDOT is the Great Salt Lake. Magnesium ions comprise only 3.7 percent of the total ions in solution in the Great Salt Lake while sodium ions comprise 32.1 percent; therefore, smaller quantities of

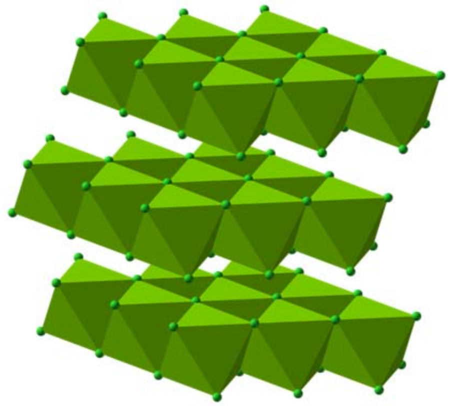

Figure 2.5 Magnesium chloride crystal lattice.

magnesium chloride are extracted each year compared to sodium chloride (*24*). Magnesium chloride is extracted as a saturated solution and handled using pumps and tanks.

Magnesium chloride is primarily applied as a saturated brine for anti-icing applications prior to storm events. Spreading rates for magnesium chloride brine are typically 30 to 40 gallons per lane mile (*25*). Because magnesium chloride has a lower effective temperature compared to sodium chloride, areas that are prone to icing, such as bridges, are often treated with a magnesium chloride brine prior to storm events. As with sodium chloride, early application is critical to ensure effective plowing and clearing of roads.

Magnesium chloride has some negative environmental impacts. Runoff of the salt into soils and waterways can be an environmental risk, especially within 60 ft of treated roads (*26*). Because magnesium chloride is a more effective deicer than sodium chloride, smaller quantities of magnesium chloride can be used, thereby reducing the overall damage to the environment by comparison.

Magnesium chloride can be very destructive to concrete structures and pavements. The primary cause of damage to concrete is the replacement of calcium in calcium-silicate-hydrate (CSH) with magnesium. CSH is formed as cement hydrates and is responsible for much of the strength of concrete. As magnesium chloride penetrates the concrete surface, the magnesium replaces the calcium, forming magnesium-silicate-hydrate (MSH). MSH has very low bonding strength and is considered a non-cementitious material. The results of a study involving the effects of magnesium chloride on concrete showed that magnesium chloride caused significant concrete crumbling and cracking (*27*). Therefore, as with sodium chloride, magnesium chloride should not be distributed in excess.

2.3.3 Abrasives

Abrasives, or deslicking grit, are materials that immediately increase the friction of the pavement surface when snow and/or ice are present. Abrasives are typically coarse sands, but slags, cinders, and bottom ashes from power plants are also used. To prevent excess moisture from freezing the abrasives together during storage, transport, and distribution, abrasives are usually blended and distributed with deicers, which also assist with the removal of ice from the pavement surface (*19*). UDOT currently uses a mixture of one part sodium chloride to one part grit by volume for their pre-mixed blends.

The quality and spreading rates of abrasives should be considered for effective use on roads. In this context, high quality abrasives are angular and typically produced during crushing of aggregates. Sands that are rounded are not as effective at increasing road surface friction, and fine sands, or those passing the No. 50 sieve, are ineffective at increasing road friction (*19, 28*). Abrasives are typically applied in quantities up to 2 cubic yards per lane mile on dangerous intersections or curves (*19*). Application should take place following a storm event to prevent the abrasives from being covered with snow and becoming ineffective.

The effectiveness of abrasives at increasing road friction is also influenced by temperature and traffic. According to one study, for road temperatures below 5°F and a spreading rate of 1000 lb per lane mile, the road friction factor increased from 0.18 to 0.40. However, the friction factor for the same surface after light trafficking (five to 10 vehicles and three to five logging trucks) decreased to 0.23 (*29*). At these temperatures, the abrasives had minimal effect on increasing the road friction following trafficking; however, the study showed that the effect of abrasives was less susceptible to trafficking at temperatures near the melting point of ice because less material was lost from the pavement surface under trafficking. At temperatures below freezing, the effectiveness of abrasives is temporary at best, and, according to another study, the best solution for increasing road friction is the use of a 2:1 ratio of abrasives to brine by volume when pavement temperatures are greater than 10°F (*30*).

Because the effect of abrasives on road friction is influenced by trafficking, engineers should consider certain factors when choosing pavement sections on which to apply abrasives. Areas with high traffic volumes or high vehicle speeds, such as freeways or major urban roads, are not ideal candidates for the use of abrasives (*31*). However, abrasives can be used on certain low-speed roads and intersections where snow pack persists (*32*).

Because abrasives do not break down under trafficking or dissolve in water, abrasives require clean up and disposal. Otherwise, excess abrasives can enter local ecosystems such as rivers, streams, and ponds or cause reduced flow rates in storm drains, sewers, and gutters. Street sweepers and vacuums are required to prevent these negative side effects of using abrasives on roads.

2.4 Summary

The primary goal of any winter maintenance operation is to economically provide safe and passable roads during the winter months. Because the transportation system is vital to industry and commerce, breakdowns in the transportation system due to snow and ice have adverse effects on local economies.

As of 2012, UDOT is responsible for maintenance of over 18,000 lane miles of roads each winter. To facilitate the task of snow and ice removal in Utah, UDOT has divided the state into 73 maintenance stations. UDOT plows state roads and spreads deicers using a dump truck fitted with plow blades. The UDOT road weather information system provides real-time information on road conditions, which is extremely useful to winter maintenance personnel, as specific knowledge regarding the severity of a winter storm enables application of the most appropriate treatments.

Deicers are ionic salts that dissolve into ions when they come in contact with water. Sodium chloride is an ionic compound formed from sodium and chlorine. In the field, the lowest effective temperature at which snow and ice can be removed using sodium chloride is approximately 15°F. The Great Salt Lake in northern Utah is the primary source of salt for UDOT, although other salt mines, such as the Redmond mine, are also used. Sodium chloride is commonly applied as a solid, but it can also be applied as a brine or be pre-wetted with either water or liquid deicers. Although sodium chloride is a naturally occurring mineral, there are detrimental effects to the environment and to pavements when it is used as a deicer on roads.

Magnesium chloride is composed of magnesium and chlorine. The lowest effective temperature for magnesium chloride when used as a deicer in the field is approximately -5°F. As with sodium chloride, the primary source of magnesium chloride for UDOT is the Great Salt Lake. Magnesium chloride is primarily applied as a saturated brine for anti-icing applications prior to storm events. Magnesium chloride also has some negative environmental impacts, and it can be very destructive to concrete structures and pavements.

Abrasives are materials that immediately increase the friction of the pavement surface when snow and/or ice are present. The quality and spreading rates of abrasives should be considered for effective use on roads. The effectiveness of abrasives at increasing road friction is also influenced by temperature and traffic. Because the effect of abrasives on road friction is influenced by trafficking, engineers should consider certain factors when choosing pavement sections on which to apply abrasives. Because abrasives do not break down under trafficking or dissolve in water, abrasives require clean up and disposal.

3.0 PROCEDURES

3.1 Overview

The following sections describe the procedures employed in this research. A discussion of data sources and compilation procedures is provided together with an explanation of the statistical analyses performed to analyze the data.

3.2 Data Sources and Compilation

As described in the following sections, three data sources were consulted and/or developed for this research: Maintenance Management Quality Assurance (MMQA) database, UDOT road database, and Google Maps. Custom software was developed to merge data from these large data sets together.

3.2.1 MMQA Database

The MMQA database contains winter maintenance information for every maintenance station in Utah. The database includes the quantities of snow and ice treatments, typically deicers, used for a given plow route on a given date. The MMQA database also includes a description of the route for the date recorded. In the database, the data are divided by maintenance station and plow route, and the deicing treatments recorded in this database are salt, Redmond salt, brine, wetted salt, magnesium chloride, sand, pre-mix, and wetted pre-mix. Salt refers to sodium chloride; Redmond salt refers to sodium chloride from the Redmond, Utah, salt mines; brine refers to sodium chloride brine; sand refers to deslicking grit, generally crushed volcanic cinders, screened sand, and expanded shale (*33*); and pre-mix refers to mixtures of sodium chloride and grit.

UDOT personnel entered approximately 281,000 unique records into the MMQA database from 2002 until the middle of 2009, when it was incorporated into a new maintenance management system with reduced input requirements. The MMQA database also contained data for the period between 1998 and 2001, but it was very limited and therefore not evaluated in this research. Although the data recorded in the MMQA database may certainly reflect policies and/or preferences in place at each of the different maintenance stations during the period of analysis, this research did not explicitly account for such policies or preferences.

3.2.2 UDOT Road Information

Specific road information such as pavement area, pavement material type, and annual average daily traffic (AADT) volume was provided by UDOT. This information was organized by state road numbers and spanned three separate databases. UDOT also provided a database that contained detailed plow route information regarding distances and roads covered. As part of the data compilation process performed in this research, these data sets were cross-referenced to each other to form a single database. Any data that contained errors or could not be cross-referenced were excluded from the research; for example, plow routes that had conflicting information regarding pavement type or length were excluded. The compiled data were later combined using computer software to determine the quantity of pavement area and percentage of pavement type for each maintenance station.

The data set containing pavement material type information for each plow route was central to the analysis of deicer usage. Without these data, alternative methods would have been necessary for determining pavement types and areas. However, such methods, including manually measuring the lengths and widths of the roads comprising each plow route from either satellite images or by driving the plow routes, for example, would have required more resources than were available for this research.

3.2.3 Google Maps

Google Maps was utilized to determine longitude, latitude, and elevation for each of the 73 maintenance stations. This information was required for the statistical analyses performed in this research. In consideration of the large geographic areas covered by the stations, a pseudo-random sampling of five locations was used to determine the average elevation and coordinates for each maintenance station. Sampling was limited to locations that were representative of the maintenance station and therefore excluded mountain peaks and other anomalous topographic features.

The pseudo-random sampling and geographic data compilation involved multiple steps. A computer randomization routine was used to select the positions of five random locations on a scalable 10 by 10 grid to allow for different maintenance station sizes. These locations were then highlighted in red, and the grid was scaled and overlaid onto an electronic version of the maintenance station map, which was provided by UDOT. The red highlighting allowed for a quick visual inspection of the locations. If a location was determined to be unrepresentative, such as a mountain peak or body of water, a new set of five random locations was generated for evaluation. This process was repeated until all locations were representative of the maintenance station. In Google Maps, the longitude, latitude, and elevation were then determined at the center of each highlighted location within the grid. An arithmetic mean was then computed to produce a single longitude, latitude, and elevation for the entire maintenance station. The sampling process is shown in Figure 3.1 for one of the 73 maintenance stations.

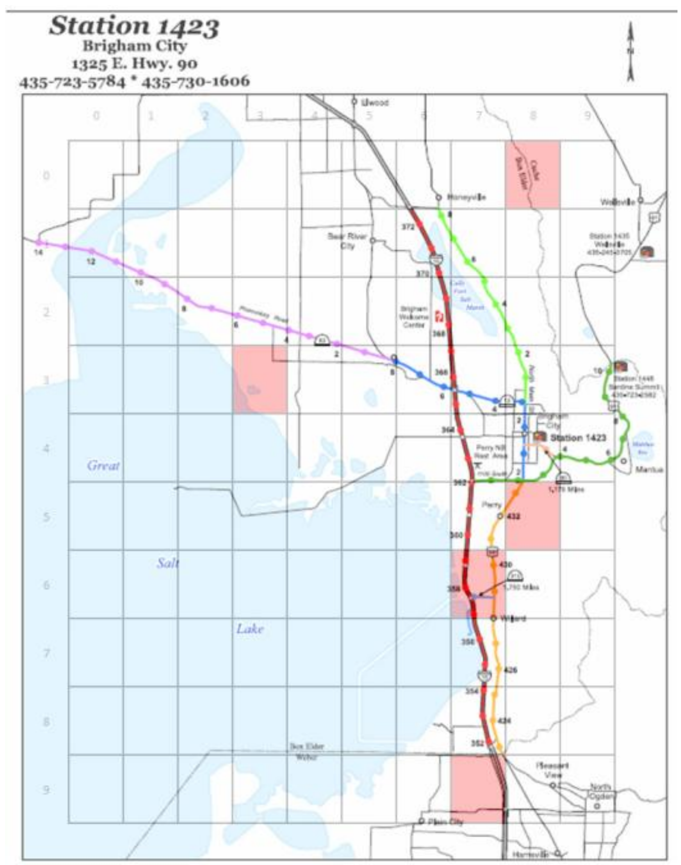

Figure 3.1 Random sampling of a maintenance station.

The geographic information gathered for each maintenance station was used in place of weather information in the analyses performed in this research. Weather data, such as air temperature, freezing degree days, and precipitation, for example, were not available for each maintenance station and therefore could not be incorporated in the modeling.

3.2.4 Data Compilation Using Developed Software

The final compiled data set prepared for analysis in this research contained deicer quantities, pavement surface areas by pavement material type, traffic, longitude, latitude, and elevation data. The compilation of this data was performed by computer software and required four steps. First, the data from the MMQA database, combined UDOT road database, and Google Maps were imported into Structured Query Language (SQL) data tables. Second, custom software was written to calculate the pavement surface area for each plow route in Utah using the MMQA database and the UDOT road database. Third, the plow route surface area data were combined with the traffic, longitude, latitude, and elevation data and plow route deicer types and quantities. Fourth, the compiled data were organized by maintenance station into a single data table.

To efficiently combine these multiple large data sets, database software and computer programming languages were used. The MySQL database software package was used to create SQL data tables for analysis in this research. Afterwards, the programming languages PHP, JavaScript, and HTML were employed, with the latter being utilized to provide a graphical user interface and also to provide tabular output of computed data.

Four SQL data tables were created using the MySQL database software. SQL data tables allow programs to systematically access and combine data effectively using standardized SQL queries. Specifically, SQL data tables were created for deicer types and quantities, pavement surface area by mile marker, pavement material type by mile marker, and plow route information. Consistency in the data table structures allowed for the software to logically link these tables by snow plow route and create a single data set. Mile marker locations were based on 2010 data from UDOT.

Custom software was written in JavaScript and PHP to compute pavement surface areas by pavement type for each plow route; the software code is provided in Appendix A. The software first downloaded a list of the plow routes, which included route lengths, state road numbers, and starting and ending mile markers. The software then iterated through each plow route, calculating the number of lane miles of concrete and asphalt pavement using the SQL data tables. The output of the software included the following: maintenance station number, plow route, state road number, starting lane marker, ending lane marker, length in miles, concrete portion in miles, asphalt portion in miles, total pavement surface area of plow route in lane miles, concrete area in lane miles, and asphalt area in lane miles. If a discrepancy existed between the various data tables with respect to starting and ending mile markers for a given section of road, the software was also programmed to quantify the error in terms of miles; however, no such errors occurred. Figure 3.2 shows a screenshot of some compiled output within the database software.

Pavement Data Fetcher 3.0

Grab

station	plow route	route	start	end	length	error	concrete	asphalt	area	concrete	asphalt
1421	1	103	0	0.21	0.21		0	0.21	0.84	0	0.84
1421	1	126	0	11.6	11.6		0	11.6	46.4	0	46.4
1421	3	37	10	12.29	2.29		0	2.29	4.58	0	4.58
1421	4	107	0	2.5	2.5		0	2.5	5	0	5
1421	2	126	11.6	21.44	9.84		0	9.84	25.342	0	25.342
1421	3	39	0	3.52	3.52		0	3.52	7.04	0	7.04
1421	2	134	11.2	12.38	1.18		0	1.18	4.634	0	4.634
1421	3	134	0	11.2	11.2		0	11.2	22.4	0	22.4
1421	2	312	0	0.58	0.58		0	0.573	1.146	0	1.146
1421	4	110	0	3.48	3.48		0	3.48	6.96	0	6.96
1421	4	37	2	10	8		0	8	16	0	16
1421	4	97	0	3.05	3.05		0	3.05	9.643	0	9.643
1421	5	107	2.5	4.49	1.99		0	1.99	3.98	0	3.98
1421	5	108	1.43	13.62	12.19		0	11.49	26.124	0	26.124
1421	5	37	0	2	2		0	2	4	0	4
1421	5	97	3.05	5.78	2.73		0	2.297	9.188	0	9.188
1422	1	203	0	6.2	6.2		0	6.137	30.685	0	30.685
1422	1	203	0	0.11	0.11		0	0.11	0.55	0	0.55
1422	1	89	344.82	347	2.18		0	2.18	13.08	0	13.08
1422	1	39	6	7.72	1.72		0	1.72	3.44	0	3.44
1422	2	235	0	4.86	4.86		0	3.202	12.808	0	12.808
1422	2	204	3.4	5.4	2		0	2	8	0	8
1422	4	26	0	3.75	3.75		0	3.724	14.896	0	14.896
1422	3	15	341.22	354.22	13		2.37	10.63	52	9.48	42.52
1422	3	39	3.54	6	2.46		0	2.46	9.77	0	9.77
1422	4	204	0	3.4	3.4		0	3.4	13.6	0	13.6

Figure 3.2 Screenshot of final database software package.

The calculated pavement surface area data, which resulted from the computer software, were then combined with the traffic, longitude, latitude, elevation, and deicer data. To aggregate the data from the plow routes within each maintenance station, the quantities of deicer by deicer type and the pavement surface area for each plow route were individually summed to create maintenance station totals for each of those respective variables. Traffic data for various plow routes were averaged for each maintenance station, with the averages being weighted by plow route surface area. The deicer data evaluated in this analysis represented the total quantities of each deicer distributed during the 8-year period during which the MMQA database was used by UDOT. The values for longitude, latitude, and elevation for each maintenance station were the averages computed from the sampling process that was described previously. Table 3.1 shows an excerpt of the data set for 12 maintenance stations, with only two deicers shown for clarity. This final data set was the basis for the statistical analyses.

Table 3.1 Excerpt of Master Maintenance Station Data Set

Maintenance Station	Salt (yd^3)	Magnesium Chloride (gal)	Total Area (lane miles)	Concrete (lane miles)	Asphalt (lane miles)	Traffic (annual average daily traffic)	Elevation (ft)	Latitude (degrees)
1421	6712	0	193	0	193	19,133	4340.4	41.1948300
1422	12490	28080	249	44	205	42,508	4342.0	41.2352464
1423	7966	48950	264	32	233	23,738	4400.2	41.4853232
1424	14799	46897	233	115	117	62,728	4333.3	41.0415286
1425	2088	20323	134	0	134	5,424	5243.4	41.2443108
1426	7628	11670	156	41	114	10,647	5578.2	40.9908166
1427	10466	4500	124	24	100	73,128	4366.2	40.8808550
1431	86	12100	277	35	242	4,967	4746.8	41.7376920
1432	376	28540	189	70	118	6,358	4422.6	41.6910616
1433	1413	35163	202	86	115	12,591	4607.6	41.7705700
1435	7038	16430	145	0	144	9,128	4664.8	41.6793988
1436	2697	26434	249	0	249	18,633	4825.6	41.8553714

3.3 Statistical Analyses

Several multiple linear regression analyses were performed to determine if concrete or asphalt pavements required different amounts of deicers during the winter seasons evaluated in this research. Multiple linear regression analysis is a statistical method for fitting a linear relationship between a dependent variable and multiple independent variables. The ordinary least squares (OLS) method was the specific regression used in this research. OLS regressions attempt to minimize the sum of the squares of the differences between the observed values and the values predicted by the regression model.

Because plow routes were not equal in total pavement area, a variable called "concrete proportion" was created. Concrete proportion is the ratio of concrete pavement area to total pavement area and was the independent variable of primary interest in this research. This variable was computed for each maintenance station.

Similarly, traffic and deicer quantities were divided by total pavement area in lane miles to account for the variation in maintenance station sizes and to allow for direct comparison of the various maintenance stations. Thus, inherent in this approach is the assumption that traffic and deicer quantities were uniform across all lanes. To better model the deicer data, logarithmic transformations were applied to the resulting deicer spreading densities. As justified in this research, a logarithmic transformation is typically used for distributions in which the difference between the maximum and minimum measurements exceeds one order of magnitude (*34*). Elevation was divided by 1000 for each maintenance station to reduce the magnitude of the calculated coefficients.

Deicer quantities required additional adjustments due to the different reporting units associated with the different deicer types. For example, in the MMQA database, brine is reported in gallons, and sodium chloride is reported in cubic yards. All the deicers used by UDOT, with the exception of magnesium chloride, are sodium-chloride-based; therefore, the quantities of these deicers were calculated in terms of equivalent cubic yards of sodium chloride. Pre-mix, as mentioned previously, is a one-to-one mixture of sodium chloride and sand by volume. To adjust the pre-mix data, all values were divided by two to determine the volume of sodium chloride placed on the road. Brine is reported in gallons and is a solution of sodium chloride at a concentration of 22.3 percent. The specific gravity of brine at this concentration is approximately 1.17 at 50°F (*35*). To convert to cubic yards of sodium chloride, the reported value was divided by 843.7 as explained in Appendix B. The amounts of magnesium chloride were also converted to equivalent cubic yards using a similar approach. Magnesium chloride is used by UDOT as a brine solution reported in gallons, with a concentration of 28.0 percent. To convert to cubic yards of magnesium chloride, the reported value was divided by 671.9 as explained in Appendix B.

After the values of the independent variables were finalized, full and reduced models were created based on the statistical significance of the respective independent variables. The independent variables used in these regression models were traffic per lane mile, elevation, latitude, and concrete proportion. The dependent variables were the natural log of the total amount of all deicers per lane mile and the natural log of the amounts of each of the eight individual deicers per lane mile; for both dependent variables, the quantities evaluated were 8-year totals, representing the total amount of each deicer used and reported in the MMQA database. With full and reduced statistical models for each of the nine dependent variables, a total of 18 regression models were developed for this research. The reduced models were created from the full models by sequentially deleting factors with p-values greater than 0.15 so that all remaining factors had p-values less than or equal to 0.15. Factors in the reduced models with p-values less than or equal to 0.05 were considered to be statistically significant. An F-value and a coefficient of determination, or R^2 value, were also calculated for each model. Models with F-values less than 0.05 were considered to be statistically significant. The R^2 value is a measure of how well a given regression equation fits the observed data, where an R^2 value of 1.0 represents a perfect fit. For this research, R^2 values greater than 0.50 were considered acceptable.

3.4 Summary

Three data sources were consulted and/or developed for this research: MMQA database, UDOT road database, and Google Maps. The MMQA database contains winter maintenance information for every maintenance station in Utah. The database includes the quantities of snow and ice treatments, typically deicers, used for a given plow route on a given date. Specific road information such as pavement area, pavement material type, and AADT volume was also provided by UDOT. All the data sets were needed for this research; however, the data set containing pavement material type information for each plow route was central to the analysis of deicer usage. Google Maps was utilized to determine longitude, latitude, and elevation for each of the 73 maintenance stations through a multi-step, pseudo-random sampling process. The final compiled data set prepared for analysis in this research contained deicer quantities, pavement surface areas by pavement material type, traffic, longitude, latitude, and elevation data. The deicer data evaluated in this analysis represented the total quantities of each deicer distributed during the 8-year period during which the MMQA database was used by UDOT.

To efficiently combine these multiple large data sets, database software and computer programming languages were used. Four SQL data tables were created using the MySQL database software, and custom software was written in JavaScript and PHP to compute pavement surface areas by pavement type for each plow route. The calculated pavement surface area data, which resulted from the computer software, were then combined with the traffic, longitude, latitude, and elevation data and deicer types and quantities.

Several multiple linear regression analyses were performed to determine if concrete or asphalt pavements required different amounts of deicers during the winter seasons evaluated in this research. Because plow routes were not equal in total pavement area, a variable called “concrete proportion” was created. Similarly, traffic and deicer quantities were divided by total pavement area in lane miles to account for the variation in maintenance station sizes and to allow for direct comparison of the various maintenance stations. Deicer quantities required additional adjustments due to the different reporting units associated with the different deicer types. After the values of the independent variables were finalized, full and reduced models were created for the total amount of all deicers per lane mile and the amounts of each of the eight individual deicers per lane mile based on the statistical significance of the respective independent variables; for both dependent variables, the quantities evaluated were 8-year totals, representing the total amount of each deicer used and reported in the MMQA database. With full and reduced statistical models for each of the nine dependent variables, a total of 18 regression models were developed for this research.

4.0 RESULTS

4.1 Overview

The results of the data compilation and statistical analysis performed in this research, together with a discussion of the findings, are provided in the following sections.

4.2 Data Compilation

The data compiled from the MMQA database, UDOT road database, and Google Maps are presented in Appendix C, which shows the raw values before any transformations or normalizations were performed; the data that were used in the statistical analysis after the transformations and normalizations were performed are presented in Appendix D. Deicer usage during the period of time analyzed in this research, which was from 2002 until the middle of 2009, is shown in Figures 4.1 and 4.2 for solid deicers and liquid deicers, respectively. The comparatively low deicer quantities shown in both figures for the year 2002 suggest that participation in the MMQA program was still limited across the state at that time; the fact that data were recorded in the MMQA database for only half of the year 2009, before the MMQA program was incorporated into the new system, is also apparent. Nonetheless, for simplicity, an 8-year duration was assumed for the data set to facilitate computation of average annual deicing quantities for each deicer type. The resulting distribution maps, which incorporate geographical information from Google Maps, are displayed in Figures 4.3 to 4.11. The variations in deicer usage across the state are likely attributable to differences in climatic conditions, the economic importance of the local roadways, deicer transportation costs, and local winter maintenance practices and/or preferences, for example.

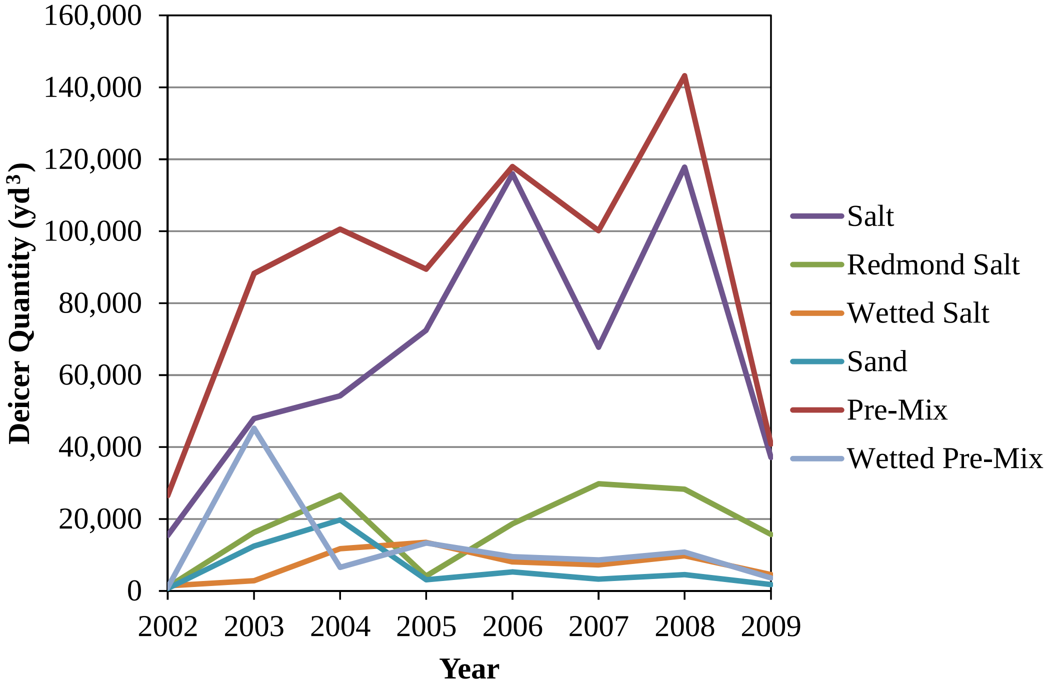

Figure 4.1 Deicer quantities by year for solid deicers.

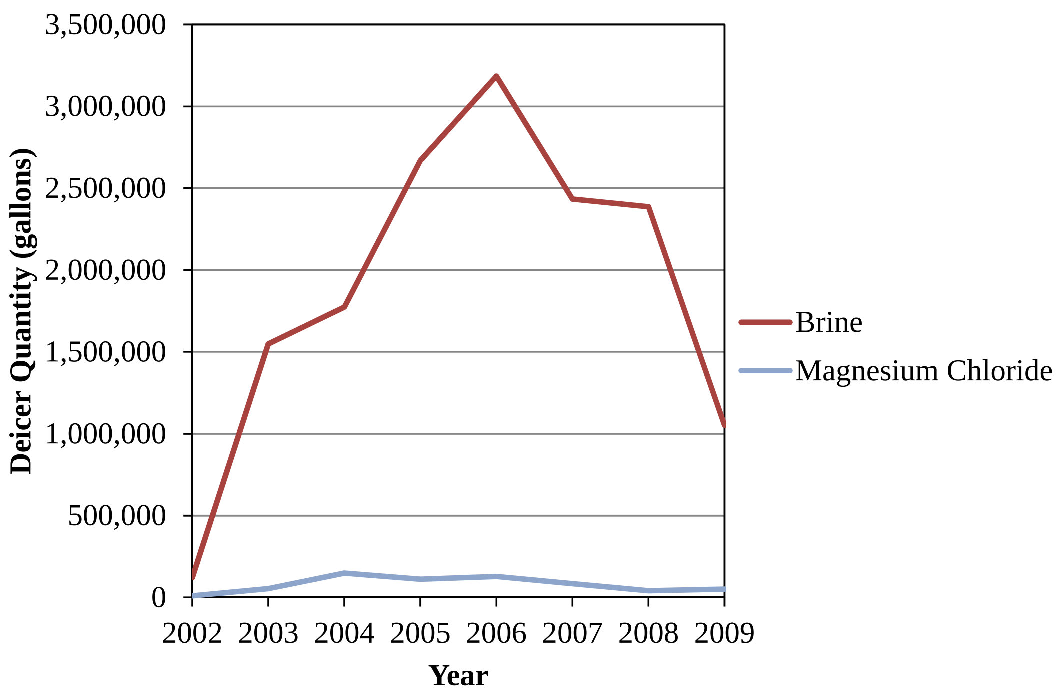

Figure 4.2 Deicer quantities by year for liquid deicers.

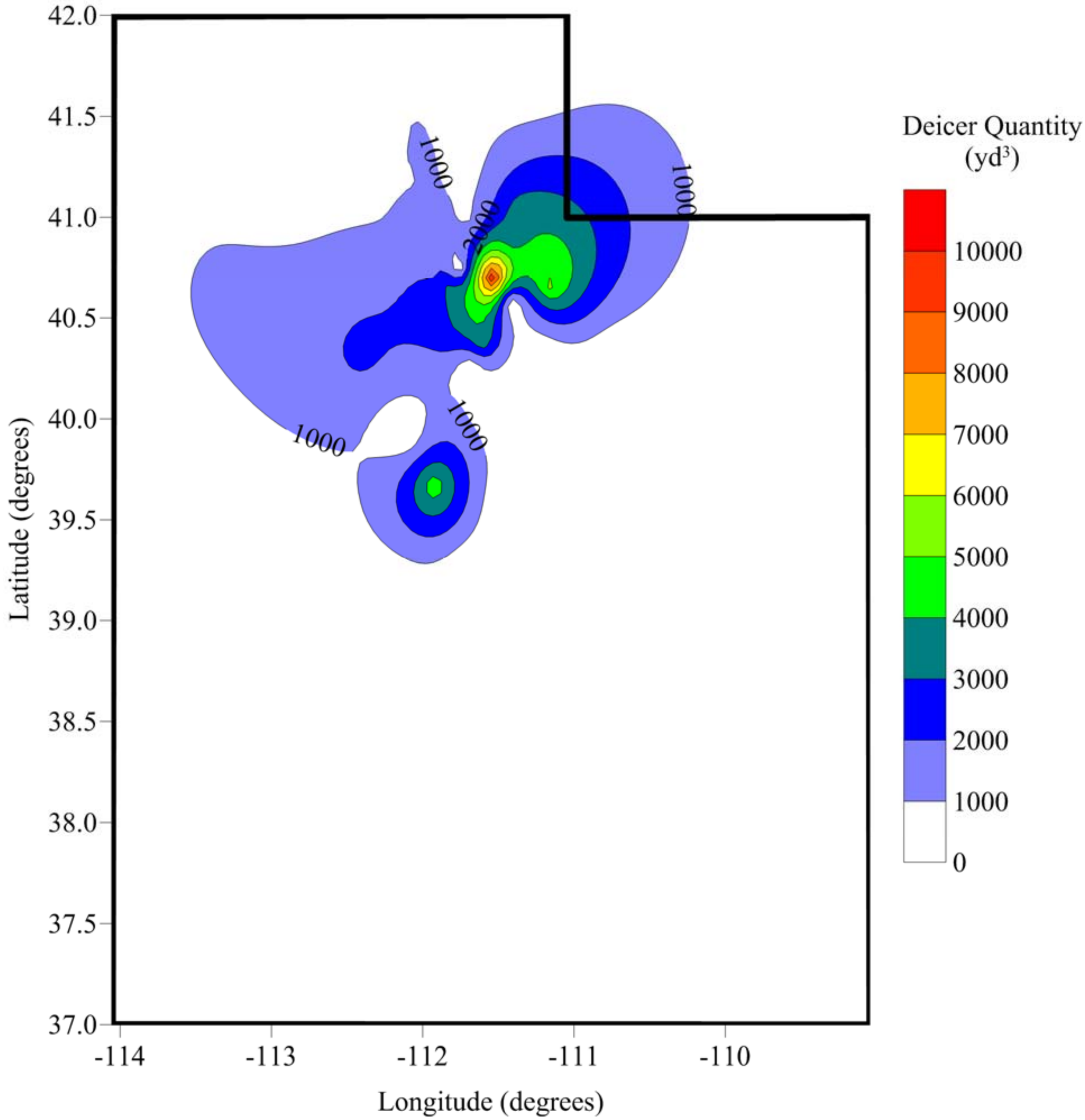

Figure 4.3 Salt distribution map.

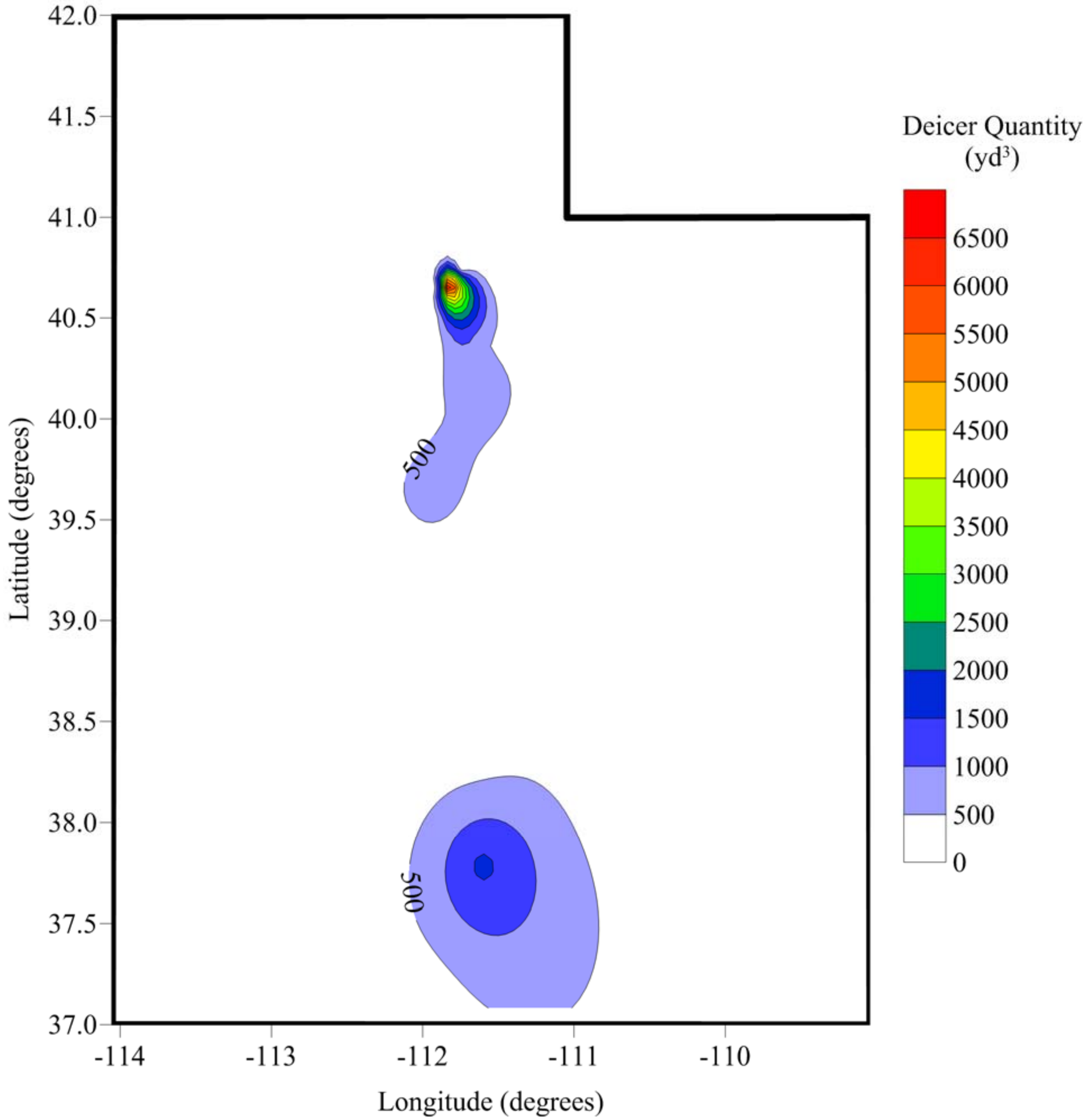

Figure 4.4 Redmond salt distribution map.

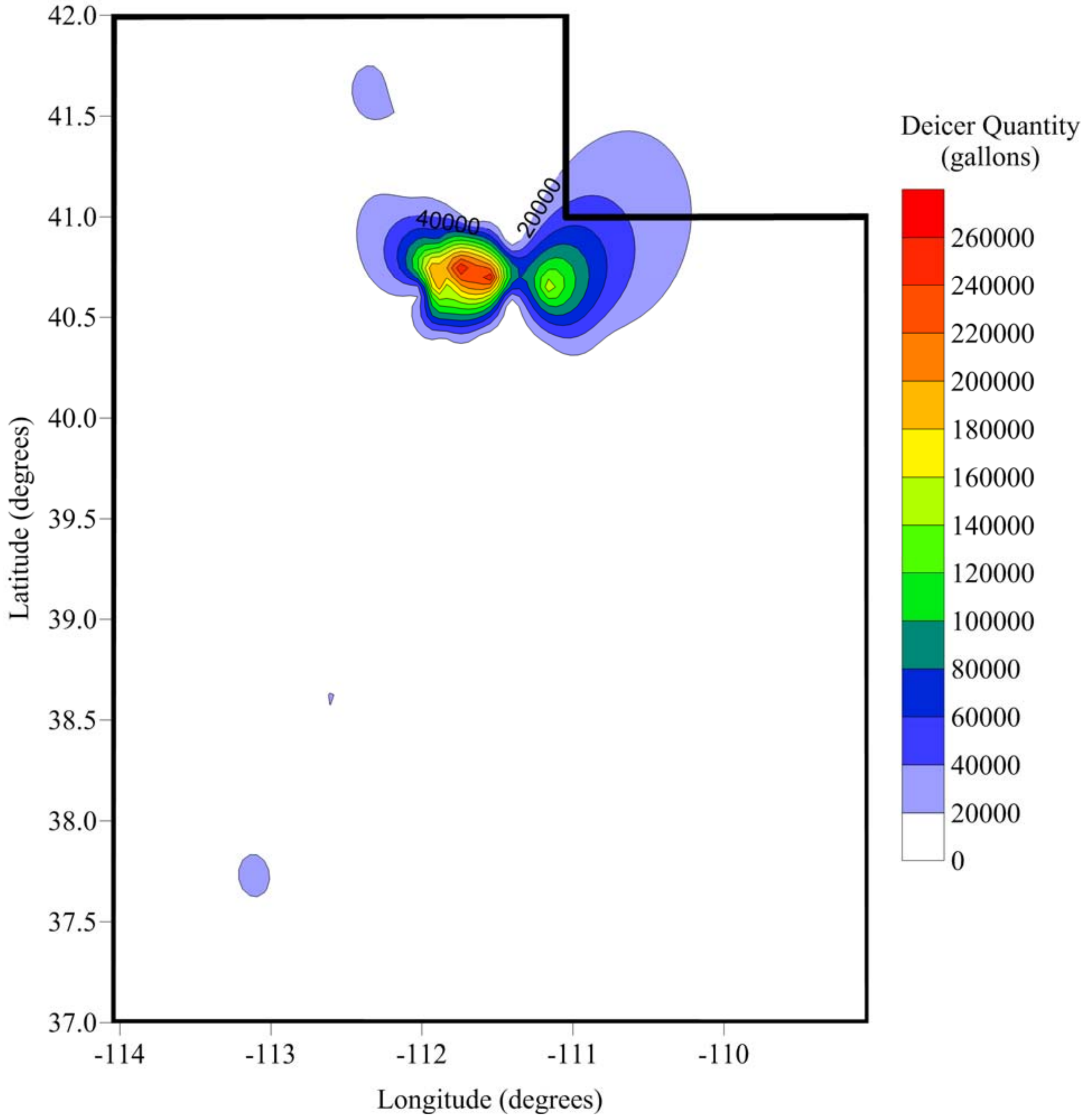

Figure 4.5 Brine distribution map.

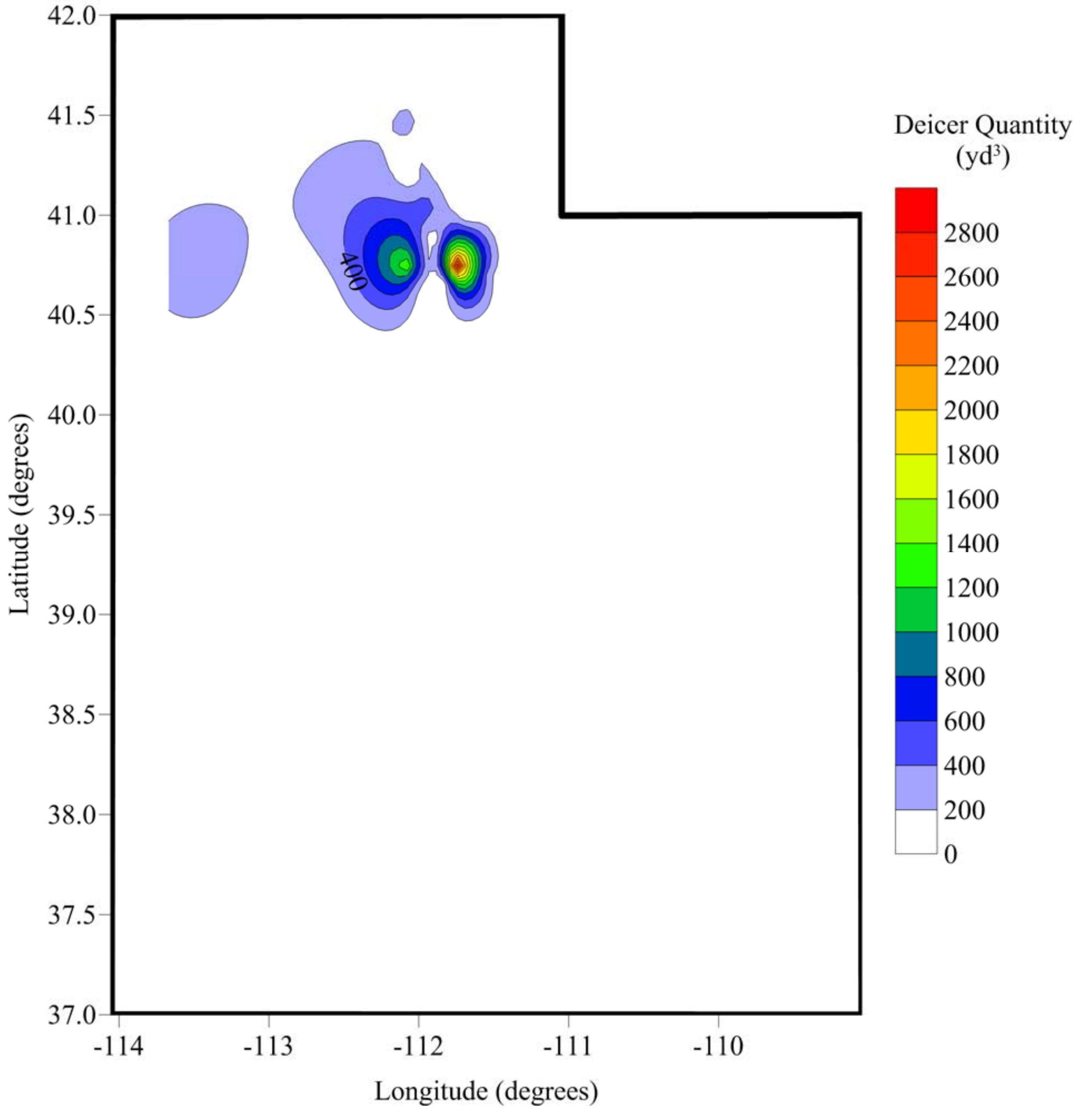

Figure 4.6 Wetted salt distribution map.

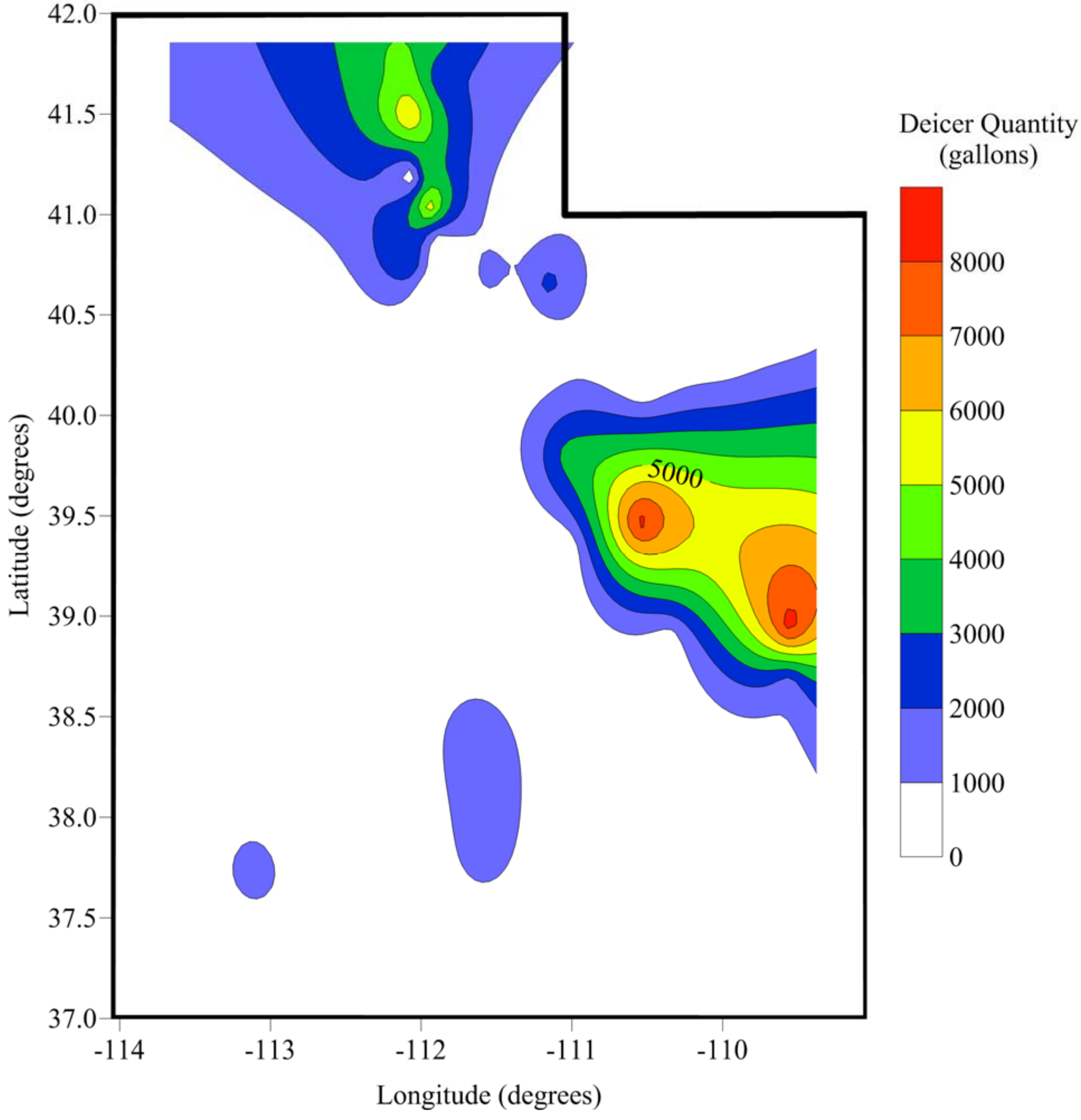

Figure 4.7 Magnesium chloride distribution map.

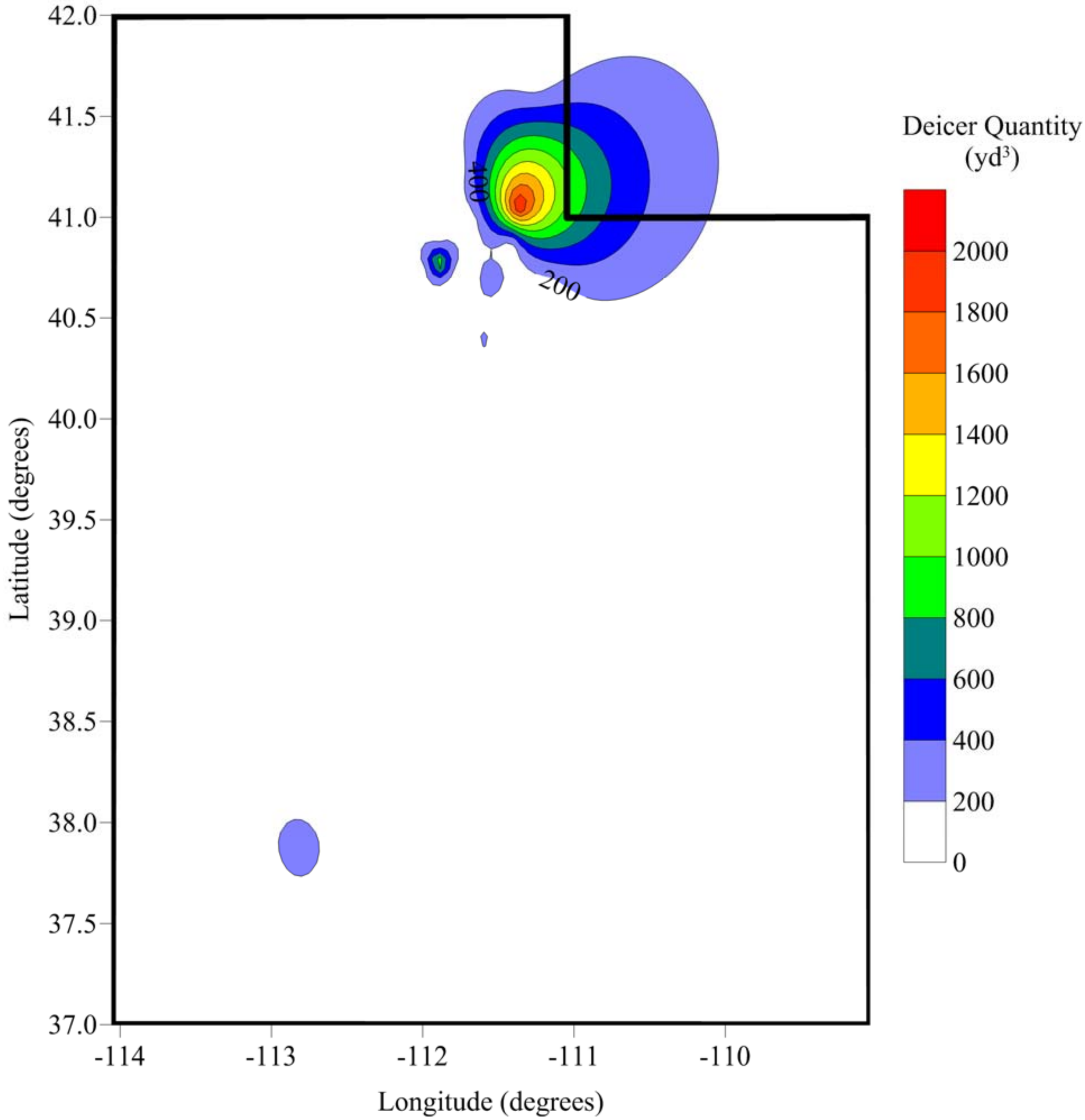

Figure 4.8 Sand distribution map.

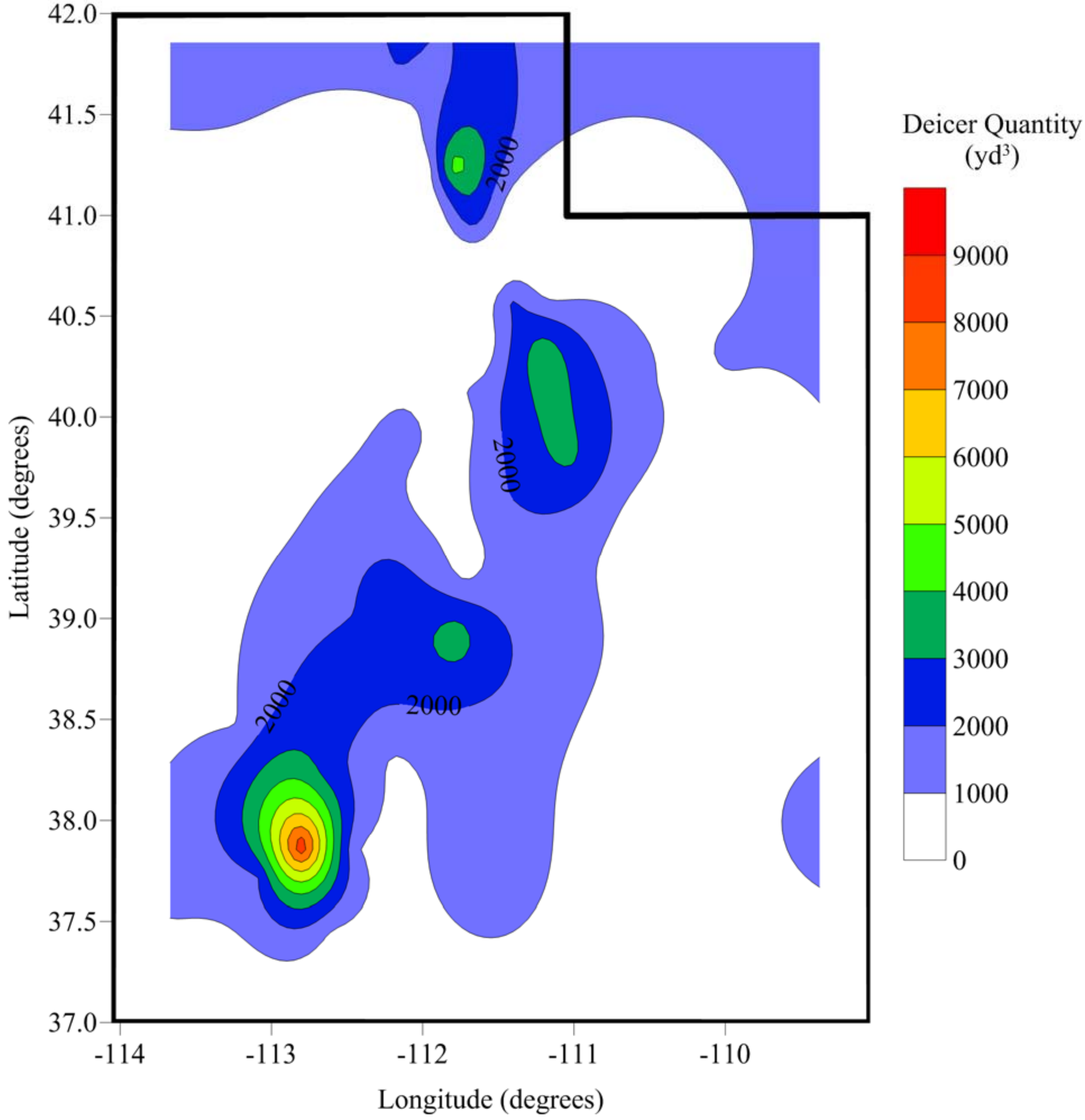

Figure 4.9 Pre-mix distribution map.

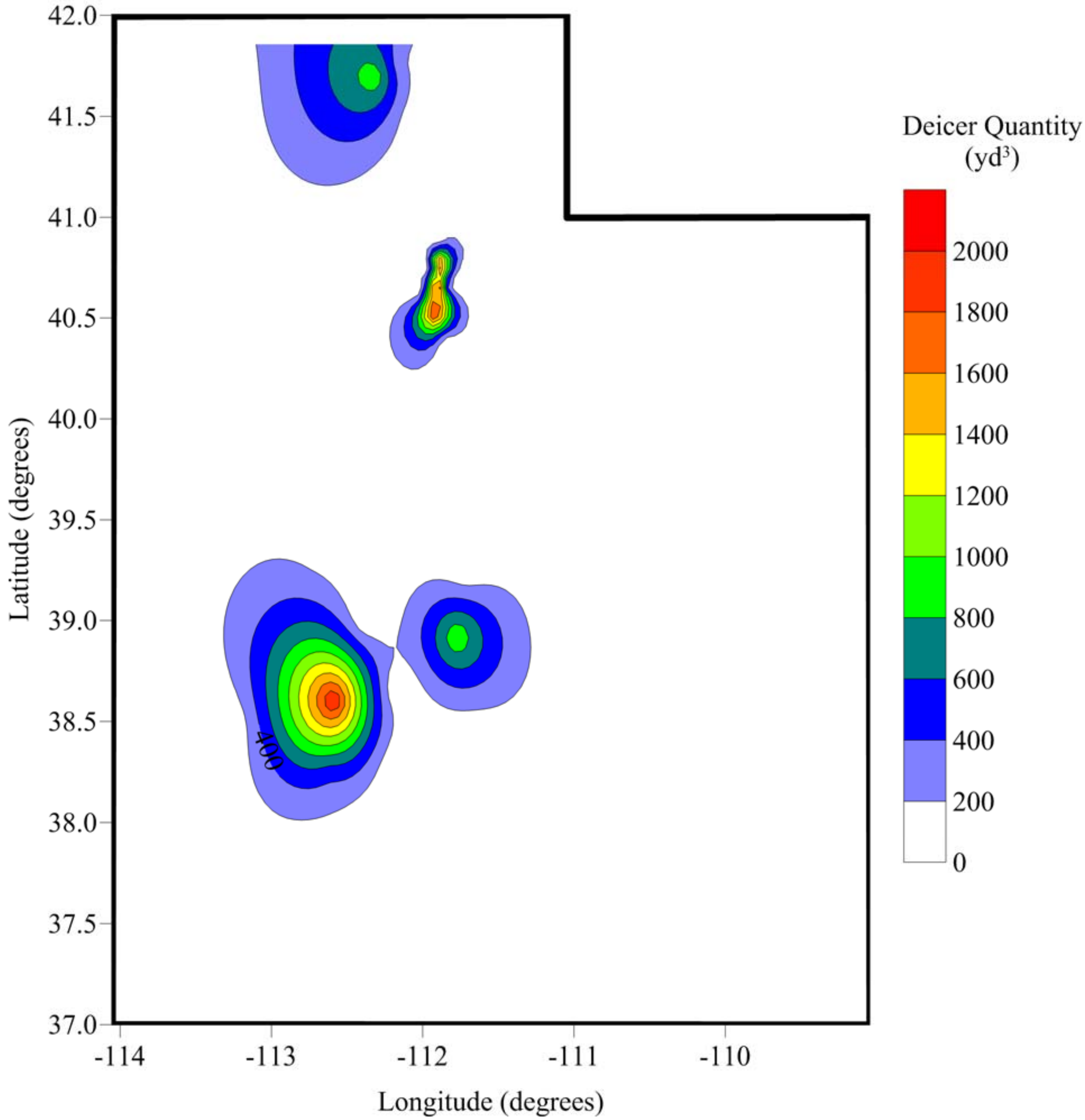

Figure 4.10 Wetted pre-mix distribution map.

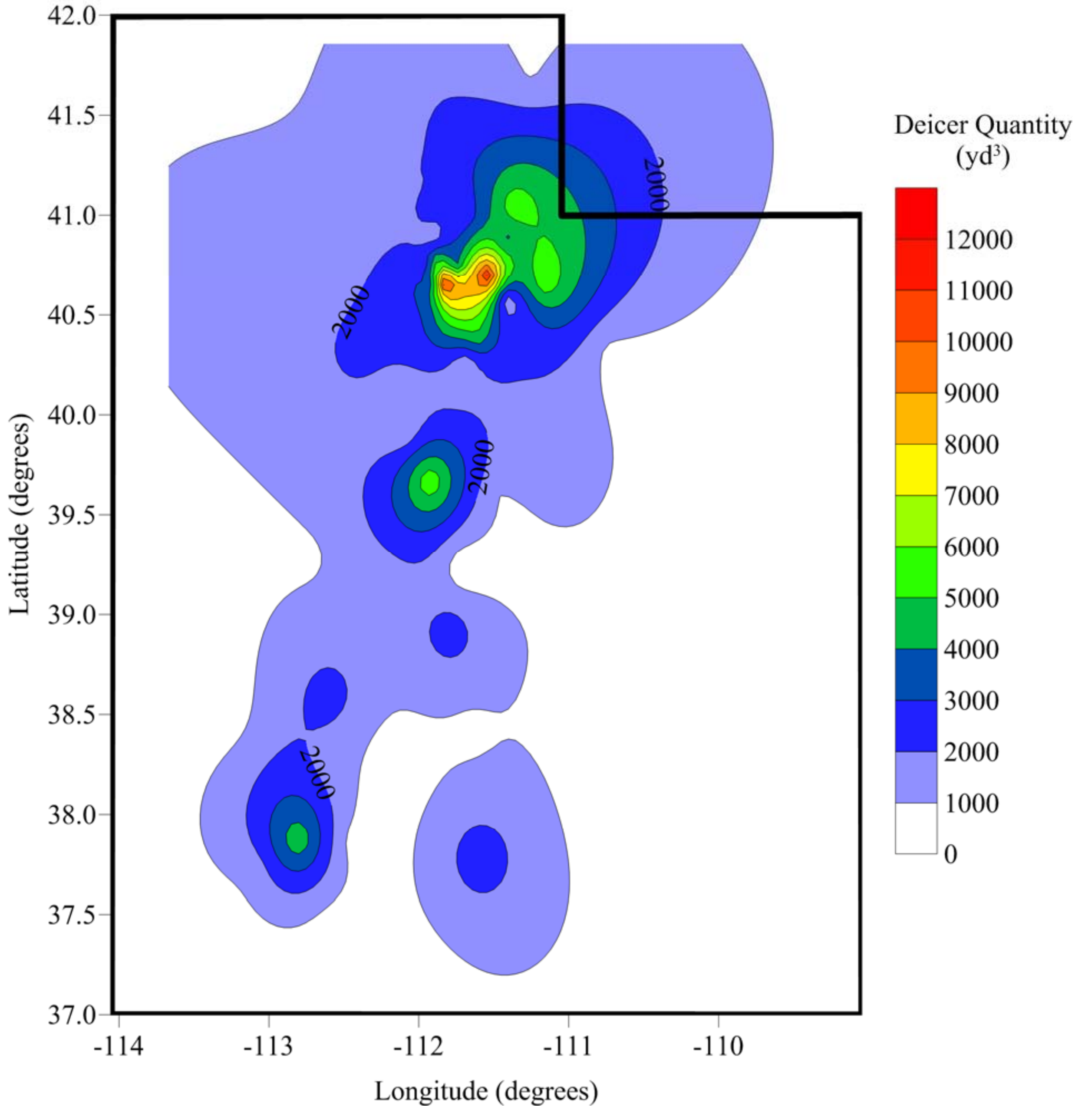

Figure 4.11 Total deicers distribution map.

4.3 Statistical Analyses

The results for the full and reduced statistical models are presented in Tables 4.1 and 4.2, respectively. Each table gives the *p*-value computed for each independent variable for each model; factors with *p*-values less than or equal to 0.05 are considered statistically significant. The *F*-values and R^2 values for each model are also shown. The sample size for each model is 73, which is the number of maintenance stations included in the analysis.

According to the *p*-values shown in Tables 4.1 and 4.2, all of the models are statistically significant except those for Redmond salt, which also have the lowest R^2 values. Although the other models are statistically significant, the R^2 values for many of them are less than 0.50; therefore, those models are not practically important. However, the models for salt, brine, and total deicer have R^2 values greater than 0.50, and these may be useful for application to local practices. These three models are presented as Equations 4.1 to 4.3, in which the coefficients are those presented in Table 4.2, as computed for the 8-year analysis period:

$$D_{salt} = -26.68 + 0.006\,T + 0.708\,L \qquad (4.1)$$

where D_{salt} = spreading rate of salt, ln(yd^3/lane mile)

T = traffic, annual average daily traffic/lane mile

L = latitude, degrees

$$D_{brine} = -1.20 + 0.004\,T + 0.204\,E + 0.869\,Cp \qquad (4.2)$$

where D_{brine} = spreading rate of brine, ln(yd^3/lane mile)

T = traffic, annual average daily traffic/lane mile

E = elevation, 1000 ft

Cp = concrete proportion

$$D_{total} = -16.678 + 0.004\,T + 0.594\,E + 0.431\,L \qquad (4.3)$$

where D_{total} = spreading rate of total deicer, ln(yd^3/lane mile)

T = traffic, annual average daily traffic/lane mile

E = elevation, 1000 ft

L = latitude, degrees

Table 4.1 Full Statistical Models

Dependent Variable	Model	Intercept		Traffic		Elevation		Latitude		Concrete Proportion		R^2
	F - value	Estimate	*p* - value	Estimate	*p* - value	Estimate	*p* - value	Estimate	*p* - value	Estimate	*p* - value	
Salt	<0.0001	-27.140	<0.0001	0.006	0.0002	0.035	0.8555	0.715	<0.0001	-0.203	0.8587	0.5337
Redmond Salt	0.3338	-3.863	0.4268	0.002	0.0794	0.170	0.3258	0.100	0.4039	-0.884	0.3948	0.0642
Brine	<0.0001	-2.712	0.1558	0.004	<0.0001	0.207	0.0030	0.038	0.4164	0.800	0.0515	0.6393
Wetted Salt	0.0014	-3.570	0.3370	0.001	0.2154	0.030	0.8229	0.093	0.3116	1.755	0.0294	0.2260
Magnesium Chloride	0.0287	-0.829	0.0131	0.000	0.1070	-0.006	0.6081	0.023	0.0050	0.063	0.3684	0.1451
Sand	<0.0001	-8.072	0.0126	0.004	<0.0001	0.302	0.0091	0.171	0.0307	-0.117	0.8625	0.3937
Pre-Mix	<0.0001	0.176	0.9721	-0.005	0.0016	0.537	0.0038	-0.008	0.9515	1.167	0.2815	0.3272
Wetted Pre-Mix	0.0102	2.092	0.5686	0.002	0.1113	0.059	0.6537	-0.055	0.5407	1.598	0.0445	0.1746
Total Deicer	<0.0001	-16.175	<0.0001	0.003	0.0001	0.605	<0.0001	0.416	<0.0001	0.613	0.3189	0.5954

Table 4.2 Reduced Statistical Models

Dependent Variable	Model	Intercept		Traffic		Elevation		Latitude		Concrete Proportion		R^2
	F - value	Estimate	*p* - value	Estimate	*p* - value	Estimate	*p* - value	Estimate	*p* - value	Estimate	*p* - value	
Salt	<0.0001	-26.680	<0.0001	0.006	<0.0001			0.708	<0.0001			0.5332
Redmond Salt	0.1233	1.005	<0.0001	0.002	0.1233							0.0331
Brine	<0.0001	-1.200	0.0028	0.004	<0.0001	0.204	0.0033			0.869	0.0307	0.6358
Wetted Salt	0.0001	0.315	0.0189							2.548	0.0001	0.1905
Magnesium Chloride	0.0040	-0.813	0.0067					0.022	0.0040			0.1111
Sand	<0.0001	-7.976	0.0117	0.004	<0.0001	0.304	0.0079	0.168	0.0287			0.3934
Pre-Mix	<0.0001	0.038	0.9703	-0.004	0.0017	0.516	0.0048					0.3153
Wetted Pre-Mix	0.0017	0.251	0.0727	0.001	0.1446					1.456	0.0565	0.1672
Total Deicer	<0.0001	-16.678	<0.0001	0.004	<0.0001	0.594	<0.0001	0.431	<0.0001			0.5894

The independent variable of interest in this study was concrete proportion; this variable accounts for the amount of concrete pavement area for a given maintenance station. Among both the full and reduced models, concrete proportion was statistically significant in the wetted salt and wetted pre-mix models, and it was also statistically significant in the reduced model for brine, the latter being shown in Equation 4.2.

4.4 Discussion

The focus of this research was to determine if there is a statistical difference in deicer usage on concrete and asphalt pavements within the state of Utah. From the results of the statistical analyses, concrete proportion is statistically significant in models for three of the dependent variables, including brine, wetted salt, and wetted pre-mix. These specific deicers comprise, on average, 9 percent of the total deicer volume applied by UDOT; however, for three maintenance stations (2424, 2434, and 4424), which include west Salt Lake City, Parley's Canyon, and Moab, respectively, these deicers constitute more than 50 percent of the total deicer volume. Furthermore, the computed concrete proportion coefficient is positively correlated with higher deicer spreading densities for these cases. Because a regression coefficient represents the amount of change in the dependent variable as a result of change in the coefficient parameter, a positive correlation indicates that an increase in the proportion of concrete pavement on a given plow route would increase the amount of these specific deicers being applied per lane mile.

If, for example, a given lane mile of pavement was constructed entirely of concrete, had an annual average daily traffic density of 103, and had an elevation of 5300 ft, the latter two values being average values for all the maintenance stations evaluated in this research, Equation 4.2 could be used to estimate the amount of brine in cubic yards of salt distributed during the course of the 8-year analysis period. In Equation 4.2, T, E, and Cp would be 103, 5.3, and 1.0, respectively, and D would then be computed as 1.16, which equals 3.2 cubic yards of brine per lane mile after accounting for the natural log. On the other hand, if a given lane mile of pavement was constructed entirely of asphalt, Cp would change to 0.0, and D would then be reduced to 0.29, which equals 1.3 cubic yards of brine per lane mile distributed during the 8-year analysis period.

Interestingly, concrete proportion was not significant in any of the models associated with dry deicer applications. Furthermore, neither the full nor the reduced regression model prepared for the sum of all deicers had concrete proportion as one of the significant variables. The absence of concrete proportion as an independent variable in these models shows that, on average, after correcting for differences in traffic volume and pavement area, deicer usage is not affected by pavement type. While these results are based on actual deicing practices and may not necessarily be ideal in every circumstance or location, this information is nonetheless important for winter maintenance activities and planning by UDOT engineers.

4.5 Summary

The data compiled from the MMQA database, UDOT road database, and Google Maps were used to create deicer distribution maps and conduct statistical analyses, including development of full and reduced statistical models. According to the results, all of the models are statistically significant except those for Redmond salt, which also have the lowest R^2 values. However, the models for salt, brine, and total deicer have R^2 values greater than 0.50, and these may be useful for application to local practices.

The independent variable of interest in this study was concrete proportion; this variable accounts for the amount of concrete pavement area for a given maintenance station. From the results of the statistical analyses, concrete proportion is statistically significant in models for three of the dependent variables, including brine, wetted salt, and wetted pre-mix. These specific deicers comprise, on average, 9 percent of the total deicer volume applied by UDOT; however, for three maintenance stations (2424, 2434, and 4424), which include west Salt Lake City, Parley's Canyon, and Moab, respectively, these deicers constitute more than 50 percent of the total deicer volume. Furthermore, the computed concrete proportion coefficient is positively correlated with higher deicer spreading densities for these cases, indicating that an increase in the proportion of concrete pavement on a given plow route would increase the amount of these specific deicers being applied per lane mile; as demonstrated in this research, the magnitude of the concrete proportion coefficient can be used to estimate deicer spreading rates.

Interestingly, concrete proportion was not significant in any of the models associated with dry deicer applications. Furthermore, neither the full nor the reduced regression model prepared for the sum of all deicers had concrete proportion as one of the significant variables. The absence of concrete proportion as an independent variable in these models shows that, on average, after correcting for differences in traffic volume and pavement area, deicer usage in Utah is not affected by pavement type.

5.0 CONCLUSION

5.1 Summary

The objectives of this research were to 1) compile UDOT's winter maintenance data to directly compare concrete and asphalt pavements with regards to deicer usage and 2) determine if there is a statistical difference in deicer usage on concrete and asphalt pavements. To this end, three data sources were consulted for this research: MMQA database, UDOT road database, and Google Maps. The final compiled data set prepared for analysis in this research contained deicer quantities by deicer type, pavement surface areas by pavement material type, traffic, longitude, latitude, and elevation data. The deicer data evaluated in this analysis represented the total quantities of each deicer distributed during the 8-year period during which the MMQA database was used by UDOT.

Several multiple linear regression analyses were performed to determine if concrete or asphalt pavements required different amounts of deicers, including salt, Redmond salt, brine, wetted salt, magnesium chloride, sand, pre-mix, and wetted pre-mix, during the winter seasons evaluated in this research. Because plow routes were not equal in total pavement area, a variable called "concrete proportion" was created. Similarly, traffic and deicer quantities were divided by total pavement area in lane miles to account for the variation in maintenance station sizes and to allow for direct comparison of the various maintenance stations. Deicer quantities required additional adjustments due to the different reporting units associated with the different deicer types. After the values of the independent variables were finalized, full and reduced models were created for the total amount of all deicers per lane mile and the amounts of each of the eight individual deicers per lane mile based on the statistical significance of the respective independent variables; for both dependent variables, the quantities evaluated were 8-year totals, representing the total amount of each deicer used and reported in the MMQA database. With full and reduced statistical models for each of the nine dependent variables, a total of 18 regression models were completed for this research.

5.2 Findings

The independent variable of interest in this study was concrete proportion; this variable accounts for the amount of concrete pavement area for a given maintenance station. From the results of the statistical analyses, concrete proportion is statistically significant in models for three of the dependent variables, including brine, wetted salt, and wetted pre-mix. These specific deicers comprise, on average, 9 percent of the total deicer volume applied by UDOT; however, for three maintenance stations (2424, 2434, and 4424), which include west Salt Lake City, Parley's Canyon, and Moab, respectively, these deicers constitute more than 50 percent of the total deicer volume. Furthermore, the computed concrete proportion coefficient is positively correlated with higher deicer spreading densities for these cases, indicating that an increase in the proportion of concrete pavement on a given plow route would increase the amount of these specific deicers being applied per lane mile; as demonstrated in this research, the magnitude of the concrete proportion coefficient can be used to estimate deicer spreading rates.

Interestingly, concrete proportion was not significant in any of the models associated with dry deicer applications. Furthermore, neither the full nor the reduced regression model prepared for the sum of all deicers had concrete proportion as one of the significant variables. The absence of concrete proportion as an independent variable in these models shows that, on average, after correcting for differences in traffic volume and pavement area, deicer usage in Utah is not affected by pavement type.

5.3 Recommendations

Although UDOT snow plow operators are spreading higher amounts of brine, wetted salt, and wetted pre-mix on highways with higher proportions of concrete pavement in Utah, the results of this research do not indicate that greater deicer quantities are being applied to concrete pavement than to asphalt pavement, on average, when all deicer types are considered. Therefore, except in areas where applications of brine, wetted salt, and wetted pre-mix are common, winter maintenance costs should not be a factor in the determination of pavement type in Utah. To minimize environmental and pavement damage, continued attention should be given to developing efficient strategies for removing snow and ice with minimal amounts of deicers.

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APPENDIX A. SOFTWARE SOURCE CODE

This appendix contains the source code for the database software used in this research. The source code was written primarily in PHP and Javascript utilizing a MySQL database.

FILE: INDEX.PHP

```
<!DOCTYPE html PUBLIC "-//W3C//DTD XHTML 1.1//EN"
"http://www.w3.org/TR/xhtml11/DTD/xhtml11.dtd">
	<html xmlns="http://www.w3.org/1999/xhtml" xml:lang="en">

	<head>
		<title>Pavement Data Fetcher 3.0</title>
		<script type="text/javascript" src="jLite.js"></script>
		<script type="text/javascript" src="plugins.js"></script>
		<script type="text/javascript">
			function getData() {
				$.post("process.php",{}, next);

				/*var route = $('input')[0].value;
				var start = $('input')[1].value;
				var end = $('input')[2].value;
				$.post("process.php", {"route": route, "start":start, "end":end}, callback)*/
			}

			function next(data) {
				eval(data);		//returns array var routes
				//var table = rowsTable(routes);
				//$("body").appendChild(table);
				var route,start,end,station,plowroute;
				for(var i in routes) {
					station = routes[i][0];
					route = routes[i][2];
					start = routes[i][3];
					end = routes[i][4];
					plowroute = routes[i][1];
					$.post("process.php", {"plowroute":plowroute, "station":station,
"route": route, "start":start, "end":end}, callback);
				}
			}

			function callback(data) {
				eval(data);
				var table = $('#resultTable');
				if(table == null) {
					var table = document.createElement('table');
					table.id = "resultTable";
					$('body').appendChild(table);
					var Row = table.insertRow(-1);
					Row.className = "header";
					forEach(['station', 'plow route','route', 'start','end','length','error',
'concrete', 'asphalt', 'area', 'concrete', 'asphalt'], function(x) {
```

```
		var Cell = Row.insertCell(-1);

		if(Cell.cellIndex > 9) {

			Cell.className = "area";

		}

		Cell.innerHTML = x;

	});
						}
						else {
							//table.deleteRow(-1);
						}
						var Row = table.insertRow(-1);
						for(var i in result) {
							var Cell = Row.insertCell(-1);
							if(Cell.cellIndex > 6) {
								Cell.className = "area";
							}
							Cell.innerHTML = result[i];
						}
						//addTotals(table);
						//addClicks(table);
					}

					function  addTotals(table) {
						var Row = table.insertRow(-1);
						Row.className = "header";
						var Cell = Row.insertCell(-1);
						Cell.colSpan = 3;
						Cell.innerHTML = "TOTAL";
						for(var i = 4; i <= 10; i++) {
							Cell = Row.insertCell(-1);
							if(Cell.cellIndex > 4) {
								Cell.className = "area";
							}
							Cell.innerHTML = sumColumn(table, i);
						}
						//Cell = Row.insertCell(-1);
						//Cell.innerHTML = wavgColumn(table);
					}

					function sumColumn(table, col) {
						col--;
						var rows = $(table).find('tr');
						var total = 0;
						var numrows = rows.length - 1; //because i add the totals row before i call this
						for (var i = 1; i < numrows; i++) {
							total += parseFloat($(rows[i]).find('td')[col].innerHTML);
						}
						//if(col == 8) return roundNumber(total,1);
						return roundNumber(total,3);
					}
```

```
function wavgColumn(table) {
        var rows = $(table).find('tr');
        var wavg = 0;
        var numrows = rows.length - 1; //because i add the totals row before i call this
        for (var i = 1; i < numrows; i++) {
                wavg += parseFloat($(rows[i]).find('td')[3].innerHTML) *
parseFloat($(rows[i]).find('td')[7].innerHTML) / sumColumn(table, 4);
        }
        return roundNumber(wavg, 2);
}

function addClicks(table) {
        $(table).find('tr').forEach(function(el) {
                el.ondblclick = function() {
                        var table = this.parentNode;
                        table.deleteRow(-1);
                        table.deleteRow(this.rowIndex);
                        addTotals(table);
                }
        });

}

function clearResults() {
        var table = $('#resultTable');
        if(table != null) {
                table.parentNode.removeChild(table);
        }
}

document.onkeydown = function(e) {
e = e || event;
if(e.keyCode == 27) {
  clearResults();
}
 if(e.keyCode == 13) {
  $('input')[0].focus();
        $('input')[0].select();
}
}

</script>
<style type="text/css">
html {
        font-family: sans-serif;
        font-size:12px;
        background:#e4e4e4;
}
body {
        width: 90%;
        background:#fff;
        border:2px solid #9a9a9a;
        margin:15px auto;
        padding: 15px;
}
```

```
		table {
			border:1px solid #C7C7C7;
			background:#fff;
		}

		table .header {
			background:#E7E7E7;
			font-weight:bold;
		}

		table td {
			padding:2px 6px;
			text-align:center;
		}

		table .odd {
			background:#F7F7F7;
		}

		table .area {
			color:#804000;
		}
		h1 {
			margin-top:0;
		}

		form {
			width: 300px;
			margin-bottom:15px;
		}

		</style>

	</head>
	<body>
		<h1>Pavement Data Fetcher 3.0</h1>
		<form onsubmit="getData(); return false;" method="post" action="#">

				<br/><input type="submit" value="Grab"/>
		</form>
		<div id="temp"></div>


	</body>
</html>
```

FILE: PROCESS.PHP

```
<?php
class sql {
	private $username="root";
	private $password="password";
	var $database="udot";
	var $host="localhost";

	function __construct() {
		$this->connect();
	}

	function connect() {
		$connection=mysql_connect ($this->host, $this->username, $this->password)
		or  die("Not connected : " . mysql_error());
		$db_selected = mysql_select_db($this->database, $connection) or die(mysql_error());
	}

	function display($table) {
		$fields = $this->fetchArray("SHOW COLUMNS FROM $table");
		echo "<h4>$table</h4>";
		echo '<table>';
		echo '<tr class="header">';
		foreach($fields as $row) {
				echo "<td>".$row['Field']."</td>";
			}
		echo '</tr>';
		$odd = true;
		$tableData = $this->fetchArray("SELECT * FROM $table");

		for($i = 0; $i < count($tableData); $i++) {
			echo $odd ? '<tr class = "odd">' : '<tr>';
			$odd = $odd ? false: true;
			foreach($tableData[$i] as $j => $value) {
				echo "<td>".$tableData[$i][$j]."</td>";
			}
			echo "</tr>";
		}
		echo '</table>';
	}

	function jsArray($array, $name) {
		$string = "var $name = [";

		for($i = 0; $i < count($array); $i++) {
			if(count($array[$i]) > 1) { //2d array
				$string .= "[";
				$first = true;
				foreach($array[$i] as $j => $value) {
					$string .= $first ? "'".$array[$i][$j]."'" : ","."'".$array[$i][$j]."'";
					$first = false;
				}
				$string .= "]";
			}
			else { //1d array
				$string .= "'".$array[$i]."'";
```

```
				}
				if((count($array) - $i) != 1) {
					$string .= ',';
				}
			}
			$string.= "];";
			echo $string;
		}

		function query($q) {
			$result = mysql_query($q) or die(mysql_error());
			return $result;
		}

		function fetch($q) {
			$result = $this->query($q);
			return mysql_fetch_array($result);
		}

		function fetchArray($q) {
			$result = $this->query($q);
			$array = array();
			$i = 0; //rows of table
			while ($row = mysql_fetch_assoc($result)) {
				foreach ($row as $key => $value) {
					$array[$i][$key] = $value;
				}
				$i++;
			}
			return $array;
		}
	}
	$db = new sql;

	$route = $_REQUEST['route'];
	$start = $_REQUEST['start'];
	$end = $_REQUEST['end'];
	$station = $_REQUEST['station'];
	$PR = $_REQUEST['plowroute'];

	if(isset($route)) {
		//grab pavement distances
		$results = array();
		$fields = $db->fetchArray("SHOW COLUMNS FROM pavements");
		$j = 0;
		foreach($fields as $row) {
			$results[0][$j++] = $row['Field'];
		}

		$i = 1; $concrete = 0; $asphalt = 0;

		$data = $db->fetchArray("SELECT * FROM pavements WHERE route = '$route'");
		foreach($data as $row) {
			//find the rows that are around the input data
			$s = $row['from'];
			$e = $row['to'];
```

```
		if($start > $s) {
			if ($start < $e) {
				//good
				$results[$i++] = $row;
				if($end < $e) { //total in
					$concrete += $row['type'] == "Concrete" ? ($end - $start) : 0;
					$asphalt += $row['type'] == "Asphalt" ? ($end - $start) : 0;
				}
				else {
					$concrete += $row['type'] == "Concrete" ? ($e - $start) : 0;
					$asphalt += $row['type'] == "Asphalt" ? ($e - $start) : 0;
				}
			}
		}
		else {
			if ($s < $end) {
				//good
				$results[$i++] = $row;
				if($e < $end) {
					$concrete += $row['type'] == "Concrete" ? ($e - $s) : 0;
					$asphalt += $row['type'] == "Asphalt" ? ($e - $s) : 0;
				}
				else {
					$concrete += $row['type'] == "Concrete" ? ($end - $s) : 0;
					$asphalt += $row['type'] == "Asphalt" ? ($end - $s) : 0;
				}
			}
		}
	}

	//grab pavement width
	$wRoute = $route;
	$lanemiles;
	while(strlen($wRoute) < 4)
		$wRoute = "0$wRoute";

	$data = $db->fetchArray("SELECT * FROM widths WHERE route LIKE '$wRoute%'");
	foreach($data as $row) {
		//find the rows that are around the input data
		$s = $row['start'];
		$e = $row['end'];
		if($start > $s) {
			if ($start < $e) {
				//good
				if($end < $e) { //total in
					$lanemiles += ($end - $start) * $row['lanes'];
				}
				else {
					$lanemiles += ($e - $start) * $row['lanes'];
				}
			}
		}
		else {
			if ($s < $end) {
				//good
				if($e < $end) {
```

```
                                        $lanemiles += ($e - $s) * $row['lanes'];
                                    }
                                    else {
                                        $lanemiles += ($end - $s) * $row['lanes'];
                                    }
                                }
                            }
                        }
                        $area = ($lanemiles);//* 12*5280)/43560; //acres
                        $conArea = $concrete/($concrete + $asphalt) * $area;
                        $aspArea = $asphalt/($concrete + $asphalt) * $area;
                        //$area = round($area,1);
                        //$conArea = round($conArea,2);
                        //$aspArea = round($aspArea,2);

                        $length = $end - $start;
                        //$error = round($asphalt+$concrete-($end-$start),2);
                        $db->jsArray(array($station, $PR, $route, $start,$end,$length,$error, $concrete, $asphalt, $area,
$conArea, $aspArea), "result");
                        //$db->jsArray($results, "contained");
            }
            else {
                        //grab pavement route information and pass it back to the js loop
            $data = $db->fetchArray("SELECT * FROM routes");
            $db->jsArray($data, "routes");

            }

?>
```

FILE: ROUTES.PHP

```
<?php
class sql {
	private $username="root";
	private $password="password";
	var $database="udot";
	var $host="localhost";

	function __construct() {
		$this->connect();
	}

	function connect() {
		$connection=mysql_connect ($this->host, $this->username, $this->password)
		or  die("Not connected : " . mysql_error());
		$db_selected = mysql_select_db($this->database, $connection) or die(mysql_error());
	}

	function display($table) {
		$fields = $this->fetchArray("SHOW COLUMNS FROM $table");
		echo "<h4>$table</h4>";
		echo '<table>';
		echo '<tr class="header">';
		foreach($fields as $row) {
				echo "<td>".$row['Field']."</td>";
			}
		echo '</tr>';
		$odd = true;
		$tableData = $this->fetchArray("SELECT * FROM $table");

		for($i = 0; $i < count($tableData); $i++) {
			echo $odd ? '<tr class = "odd">' : '<tr>';
			$odd = $odd ? false: true;
			foreach($tableData[$i] as $j => $value) {
				echo "<td>".$tableData[$i][$j]."</td>";
			}
			echo "</tr>";
		}
		echo '</table>';
	}

	function jsArray($array, $name) {
		$string = "var $name = [";

		for($i = 0; $i < count($array); $i++) {
			if(count($array[$i]) > 1) { //2d array
				$string .= "[";
				$first = true;
				foreach($array[$i] as $j => $value) {
					$string .= $first ? $array[$i][$j] : ",".$array[$i][$j];
					$first = false;
				}
				$string .= "]";
			}
			else { //1d array
```

```
					$string .= $array[$i];
				}
				if((count($array) - $i) != 1) {
					$string .= ',';
				}
			}
			$string.= "];";
			echo $string;
		}

		function query($q) {
			$result = mysql_query($q) or die(mysql_error());
			return $result;
		}

		function fetch($q) {
			$result = $this->query($q);
			return mysql_fetch_array($result);
		}

		function fetchArray($q) {
			$result = $this->query($q);
			$array = array();
			$i = 0; //rows of table
			while ($row = mysql_fetch_assoc($result)) {
				foreach ($row as $key => $value) {
					$array[$i][$key] = $value;
				}
				$i++;
			}
			return $array;
		}
	}
	$db = new sql;

	$route = $_REQUEST['route'];
	$start = $_REQUEST['start'];
	$end = $_REQUEST['end'];

	print("you made it");
	if(isset($route)) {
		//grab pavement distances
		$results = array();
		$fields = $db->fetchArray("SHOW COLUMNS FROM pavements");
		$j = 0;
		foreach($fields as $row) {
			$results[0][$j++] = $row['Field'];
		}

		$i = 1; $concrete = 0; $asphalt = 0;

		$data = $db->fetchArray("SELECT * FROM pavements WHERE route = '$route'");
		foreach($data as $row) {
			//find the rows that are around the input data
			$s = $row['from'];
			$e = $row['to'];
```

```
		if($start > $s) {
			if ($start < $e) {
				//good
				$results[$i++] = $row;
				if($end < $e) { //total in
					$concrete += $row['type'] == "Concrete" ? ($end - $start) : 0;
					$asphalt += $row['type'] == "Asphalt" ? ($end - $start) : 0;
				}
				else {
					$concrete += $row['type'] == "Concrete" ? ($e - $start) : 0;
					$asphalt += $row['type'] == "Asphalt" ? ($e - $start) : 0;
				}
			}
		}
		else {
			if ($s < $end) {
				//good
				$results[$i++] = $row;
				if($e < $end) {
					$concrete += $row['type'] == "Concrete" ? ($e - $s) : 0;
					$asphalt += $row['type'] == "Asphalt" ? ($e - $s) : 0;
				}
				else {
					$concrete += $row['type'] == "Concrete" ? ($end - $s) : 0;
					$asphalt += $row['type'] == "Asphalt" ? ($end - $s) : 0;
				}
			}
		}
	}

	//grab pavement width
	$wRoute = $route;
	$lanemiles;
	while(strlen($wRoute) < 4)
		$wRoute = "0$wRoute";

	$data = $db->fetchArray("SELECT * FROM widths WHERE route LIKE '$wRoute%'");
	foreach($data as $row) {
		//find the rows that are around the input data
		$s = $row['start'];
		$e = $row['end'];
		if($start > $s) {
			if ($start < $e) {
				//good
				if($end < $e) { //total in
					$lanemiles += ($end - $start) * $row['lanes'];
				}
				else {
					$lanemiles += ($e - $start) * $row['lanes'];
				}
			}
		}
		else {
			if ($s < $end) {
				//good
				if($e < $end) {
```

```
								$lanemiles += ($e - $s) * $row['lanes'];
							}
							else {
								$lanemiles += ($end - $s) * $row['lanes'];
							}
						}
					}
				}
				$area = ($lanemiles * 12*5280)/43560; //acres
				$conArea = $concrete/($concrete + $asphalt) * $area;
				$aspArea = $asphalt/($concrete + $asphalt) * $area;
				$area = round($area,1);
				$conArea = round($conArea,2);
				$aspArea = round($aspArea,2);

				$length = $end - $start;
				$error = $asphalt+$concrete-($end-$start);
				$db->jsArray(array($route, $start,$end,$length,$error, $concrete, $asphalt, $area, $conArea,
$aspArea), "result");
				//$db->jsArray($results, "contained");
		}

?>
```

APPENDIX B. DEICER CONVERSION CALCULATIONS

Equation B.1 presents the factor used in this research for converting gallons of liquid deicer to cubic yards of solid deicer:

$$F = \frac{27\ G_b}{0.1337\ G_s C_s} \tag{B.1}$$

where F = conversion factor, gallons of liquid deicer/yd^3 of solid deicer

G_s = specific gravity of liquid deicer

C_s = concentration of solution of liquid deicer, %

G_b = specific gravity of solid deicer in bulk form

A conservative specific gravity for the solid deicer in bulk form was used due to the margin of error in solution concentrations and salt grain size.

Sodium Chloride Brine *F*

G_s = 1.17

C_s = 0.223

G_b = 1.09

F = 843.7 (gallons of sodium chloride brine/yd^3 of solid sodium chloride)

Magnesium Chloride Brine *F*

G_s = 1.17

C_s = 0.28

G_b = 1.09

F = 671.9 (gallons of magnesium chloride brine/yd^3 of solid magnesium chloride)

APPENDIX C. COMPILED DATA

The data set compiled in this research is presented in Table C.1.

Table C.1 Compiled Data

Description	Maintenance Station			
	1421	1422	1423	1424
Salt (yd^3)	6,712	12,490	7,966	14,799
Redmond Salt (yd^3)	52	0	414	149
Brine (gal)	20,330	111,385	163,618	239,065
Wetted Salt (yd^3)	210	1,834	1,944	4,251
Magnesium Chloride (gal)	0	28,080	48,950	46,897
Sand (yd^3)	744	1,506	327	1,060
Pre-Mix (yd^3)	34	395	5,001	809
Wetted Pre-Mix (yd^3)	0	89	397	0
Concrete Surface Area (lane miles)	0.0	44.0	31.7	115.2
Asphalt Surface Area (lane miles)	193.3	205.0	232.7	117.3
Total Pavement Surface Area (lane miles)	193.3	249.0	264.4	232.6
Concrete Proportion	0.000	0.177	0.120	0.496
Traffic (annual average daily traffic)	19,133	42,508	23,738	62,728
Elevation (ft)	4,340	4,342	4,400	4,333
Latitude (degrees)	41.1948300	41.2352464	41.4853232	41.0415286
Longitude (degrees)	112.0579374	111.9910584	112.0762026	111.9479370

Table C.1 Continued

Description	Maintenance Station			
	1425	**1426**	**1427**	**1431**
Salt (yd^3)	2,088	7,628	10,466	86
Redmond Salt (yd^3)	460	241	98	12
Brine (gal)	12,400	0	636,250	21,900
Wetted Salt (yd^3)	0	14	1	0
Magnesium Chloride (gal)	20,323	11,670	4,500	12,100
Sand (yd^3)	30	775	934	8
Pre-Mix (yd^3)	36,322	20,864	8	12,692
Wetted Pre-Mix (yd^3)	0	0	0	16
Concrete Surface Area (lane miles)	0.0	41.3	24.4	34.6
Asphalt Surface Area (lane miles)	134.1	114.1	99.8	242.3
Total Pavement Surface Area (lane miles)	134.1	155.4	124.2	276.9
Concrete Proportion	0.000	0.266	0.196	0.125
Traffic (annual average daily traffic)	5,424	10,647	73,128	4,967
Elevation (ft)	5,243	5,578	4,366	4,747
Latitude (degrees)	41.2443108	40.9908166	40.8808550	41.7376920
Longitude (degrees)	111.7959138	111.6719056	111.9003524	113.3305664

Table C.1 Continued

Description	Maintenance Station 1432	1433	1435	1436
Salt (yd^3)	376	1,413	7,038	2,697
Redmond Salt (yd^3)	0	113	144	376
Brine (gal)	190,436	69,967	15,457	2,841
Wetted Salt (yd^3)	532	116	0	9
Magnesium Chloride (gal)	28,540	35,163	16,430	26,434
Sand (yd^3)	8	0	74	147
Pre-Mix (yd^3)	10,562	17,269	14,887	15,552
Wetted Pre-Mix (yd^3)	7,634	2,047	12	674
Concrete Surface Area (lane miles)	70.5	86.4	0.0	0.0
Asphalt Surface Area (lane miles)	118.1	115.4	144.5	248.5
Total Pavement Surface Area (lane miles)	188.6	201.8	144.5	248.5
Concrete Proportion	0.374	0.428	0.000	0.000
Traffic (annual average daily traffic)	6,358	12,591	9,128	18,633
Elevation (ft)	4,423	4,608	4,665	4,826
Latitude (degrees)	41.6910616	41.7705700	41.6793988	41.8553714
Longitude (degrees)	112.3052672	112.1588746	111.8713760	111.8682860

Table C.1 Continued

Description	Maintenance Station 1437	2421	2422	2423
Salt (yd^3)	0	9,042	10,435	19,191
Redmond Salt (yd^3)	0	0	600	141
Brine (gal)	3,470	35,010	0	0
Wetted Salt (yd^3)	5	2,275	0	0
Magnesium Chloride (gal)	9,185	1,600	0	0
Sand (yd^3)	0	40	374	334
Pre-Mix (yd^3)	14,437	0	10	20
Wetted Pre-Mix (yd^3)	208	16	0	0
Concrete Surface Area (lane miles)	9.1	0.0	28.6	0.0
Asphalt Surface Area (lane miles)	159.1	308.7	204.2	215.4
Total Pavement Surface Area (lane miles)	168.2	308.7	232.8	215.4
Concrete Proportion	0.054	0.000	0.123	0.000
Traffic (annual average daily traffic)	1,253	7,814	19,670	8,481
Elevation (ft)	6,598	4,320	4,492	5,146
Latitude (degrees)	41.6936680	40.7376832	40.6029818	40.3223328
Longitude (degrees)	111.2555238	113.3687440	112.6708374	112.4041444

Table C.1 Continued

Description	Maintenance Station			
	2424	2425	2427	2430
Salt (yd^3)	8,343	16,099	18,478	10,793
Redmond Salt (yd^3)	503	1,397	424	32
Brine (gal)	733,400	1,429,050	760,210	1,586,118
Wetted Salt (yd^3)	11,367	0	483	2,651
Magnesium Chloride (gal)	24,200	0	0	7,208
Sand (yd^3)	288	9,572	429	2,556
Pre-Mix (yd^3)	85	3,636	8	2,124
Wetted Pre-Mix (yd^3)	297	17,399	16,299	264
Concrete Surface Area (lane miles)	117.6	77.5	150.7	100.7
Asphalt Surface Area (lane miles)	109.3	159.2	104.7	41.6
Total Pavement Surface Area (lane miles)	226.9	236.8	255.4	142.3
Concrete Proportion	0.518	0.328	0.590	0.708
Traffic (annual average daily traffic)	49,820	109,221	65,732	72,718
Elevation (ft)	4,236	4,319	4,551	4,265
Latitude (degrees)	40.7479808	40.7714148	40.5202172	40.7572058
Longitude (degrees)	112.0783998	111.9060860	111.9199218	111.9462548

Table C.1 Continued

Description	Maintenance Station			
	2431	2432	2433	2434
Salt (yd^3)	22,574	18,272	25,987	2,056
Redmond Salt (yd^3)	157	1,309	62,995	0
Brine (gal)	122,000	1,648,000	1,145,940	2,133,400
Wetted Salt (yd^3)	1,686	146	60	23,617
Magnesium Chloride (gal)	5,000	0	0	17
Sand (yd^3)	311	1,279	511	210
Pre-Mix (yd^3)	876	0	1,254	0
Wetted Pre-Mix (yd^3)	68	16,208	90	1,113
Concrete Surface Area (lane miles)	63.6	100.2	57.2	16.4
Asphalt Surface Area (lane miles)	136.2	90.8	107.1	101.9
Total Pavement Surface Area (lane miles)	199.8	191.0	164.3	118.3
Concrete Proportion	0.318	0.525	0.348	0.139
Traffic (annual average daily traffic)	37,443	131,677	43,925	46,422
Elevation (ft)	4,676	4,306	4,549	5,467
Latitude (degrees)	40.6317568	40.6525598	40.6650386	40.7450052
Longitude (degrees)	112.0098724	111.9036140	111.8270188	111.7534102

Table C.1 Continued

Description	Maintenance Station			
	2435	2436	2437	2438
Salt (yd^3)	82,446	28,130	42,102	27,784
Redmond Salt (yd^3)	1,244	574	518	1,731
Brine (gal)	2,086,643	10,360	1,262,081	0
Wetted Salt (yd^3)	2,218	0	468	0
Magnesium Chloride (gal)	13,700	3,500	19,300	0
Sand (yd^3)	2,969	493	757	16,694
Pre-Mix (yd^3)	0	68	1,476	0
Wetted Pre-Mix (yd^3)	0	0	47	0
Concrete Surface Area (lane miles)	23.3	0.0	0.0	0.0
Asphalt Surface Area (lane miles)	112.6	110.7	195.5	161.8
Total Pavement Surface Area (lane miles)	135.9	110.7	195.5	161.8
Concrete Proportion	0.171	0.000	0.000	0.000
Traffic (annual average daily traffic)	33,499	12,596	3,421	12,437
Elevation (ft)	7,018	5,825	7,622	5,845
Latitude (degrees)	40.6978254	40.8727866	40.6538238	41.0474324
Longitude (degrees)	111.5368080	111.4185334	111.1592558	111.3707426

Table C.1 Continued

Description	Maintenance Station 3421	3422	3423	3424
Salt (yd^3)	3	38,114	20,292	10,549
Redmond Salt (yd^3)	1,992	7,224	4,721	4,521
Brine (gal)	0	0	87,105	0
Wetted Salt (yd^3)	0	355	175	0
Magnesium Chloride (gal)	25	0	0	0
Sand (yd^3)	3	648	109	180
Pre-Mix (yd^3)	11,636	3,230	8,038	334
Wetted Pre-Mix (yd^3)	0	0	358	0
Concrete Surface Area (lane miles)	0.0	97.5	0.9	0.0
Asphalt Surface Area (lane miles)	155.1	224.0	245.5	131.3
Total Pavement Surface Area (lane miles)	155.1	321.5	246.4	131.3
Concrete Proportion	0.000	0.303	0.004	0.000
Traffic (annual average daily traffic)	1,049	10,788	41,846	16,687
Elevation (ft)	5,305	5,199	4,588	4,699
Latitude (degrees)	39.9159980	39.6681164	40.3902772	40.0443110
Longitude (degrees)	112.1007844	111.9270628	111.8559264	111.7698214

Table C.1 Continued

Description	Maintenance Station			
	3425	3426	3427	3431
Salt (yd^3)	30,679	1,720	2,565	39
Redmond Salt (yd^3)	4,269	6,960	7,355	103
Brine (gal)	1,930	0	1,400	400
Wetted Salt (yd^3)	42	0	0	4
Magnesium Chloride (gal)	0	0	5,200	150
Sand (yd^3)	1,906	0	5	9
Pre-Mix (yd^3)	851	10,837	0	17,269
Wetted Pre-Mix (yd^3)	0	19	0	220
Concrete Surface Area (lane miles)	21.9	0.1	11.9	27.1
Asphalt Surface Area (lane miles)	76.9	211.1	187.0	95.6
Total Pavement Surface Area (lane miles)	98.8	211.2	198.9	122.7
Concrete Proportion	0.222	0.001	0.060	0.221
Traffic (annual average daily traffic)	23,290	18,781	66,948	10,119
Elevation (ft)	5,911	4,591	4,610	6,199
Latitude (degrees)	40.3802766	40.1157300	40.2674602	40.5794706
Longitude (degrees)	111.6039276	111.6765746	111.6887972	111.4207308

Table C.1 Continued

Description	Maintenance Station			
	3433	3434	3435	3437
Salt (yd^3)	13	18	194	558
Redmond Salt (yd^3)	3	14	990	21
Brine (gal)	0	0	0	10,500
Wetted Salt (yd^3)	0	0	0	0
Magnesium Chloride (gal)	0	0	0	0
Sand (yd^3)	358	0	40	49
Pre-Mix (yd^3)	11,256	8,649	8,322	8,471
Wetted Pre-Mix (yd^3)	0	0	0	0
Concrete Surface Area (lane miles)	0.0	0.0	0.0	0.0
Asphalt Surface Area (lane miles)	141.7	132.3	189.4	189.7
Total Pavement Surface Area (lane miles)	141.7	132.3	189.4	189.7
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic)	986	2,434	5,975	5,666
Elevation (ft)	6,639	6,334	5,408	5,890
Latitude (degrees)	40.3188554	40.1412196	40.3144660	40.5037490
Longitude (degrees)	110.7333984	110.5328978	109.9953920	109.4723052

Table C.1 Continued

Description	Maintenance Station			
	3445	**4321**	**4322**	**4324**
Salt (yd^3)	176	0	0	0
Redmond Salt (yd^3)	2,938	10	0	13,301
Brine (gal)	11,206	0	0	20
Wetted Salt (yd^3)	0	0	0	51
Magnesium Chloride (gal)	0	0	0	9,726
Sand (yd^3)	692	170	0	0
Pre-Mix (yd^3)	29,617	2,151	5,217	14,998
Wetted Pre-Mix (yd^3)	0	0	0	293
Concrete Surface Area (lane miles)	0.0	0.0	0.0	0.0
Asphalt Surface Area (lane miles)	86.4	148.8	123.7	207.9
Total Pavement Surface Area (lane miles)	86.4	148.8	123.7	207.9
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic)	3,030	4,187	1,867	1,490
Elevation (ft)	6,973	4,865	6,825	6,748
Latitude (degrees)	40.3180994	37.0821092	37.4218294	37.7888264
Longitude (degrees)	111.2019652	112.0257096	112.5874638	111.6070862

Table C.1 Continued

Description	Maintenance Station			
	4325	4326	4327	4328
Salt (yd^3)	0	0	20	84
Redmond Salt (yd^3)	15	0	536	46
Brine (gal)	0	200	33,364	0
Wetted Salt (yd^3)	0	0	0	0
Magnesium Chloride (gal)	0	0	16	0
Sand (yd^3)	10	40	0	32
Pre-Mix (yd^3)	8,805	6,545	18,000	4,250
Wetted Pre-Mix (yd^3)	70	0	0	0
Concrete Surface Area (lane miles)	0.0	0.0	229.0	0.0
Asphalt Surface Area (lane miles)	154.4	130.4	117.5	99.6
Total Pavement Surface Area (lane miles)	154.4	130.4	346.6	99.6
Concrete Proportion	0.000	0.000	0.661	0.000
Traffic (annual average daily traffic)	4,412	960	6,050	7,019
Elevation (ft)	6,953	6,198	5,869	5,340
Latitude (degrees)	37.8635112	38.2772736	38.6620680	39.2437940
Longitude (degrees)	112.4431456	112.1875762	112.1772766	111.7196962

Table C.1 Continued

Description	Maintenance Station			
	4331	4332	4333	4334
Salt (yd^3)	8	0	174	33
Redmond Salt (yd^3)	0	0	1,039	167
Brine (gal)	13,241	0	0	0
Wetted Salt (yd^3)	0	0	1,403	0
Magnesium Chloride (gal)	13,240	0	102	0
Sand (yd^3)	0	0	0	8
Pre-Mix (yd^3)	11,673	1,022	28,495	15,077
Wetted Pre-Mix (yd^3)	0	0	8,055	8
Concrete Surface Area (lane miles)	0.0	0.0	2.0	0.0
Asphalt Surface Area (lane miles)	271.1	247.7	305.4	186.7
Total Pavement Surface Area (lane miles)	271.1	247.7	307.4	186.7
Concrete Proportion	0.000	0.000	0.006	0.000
Traffic (annual average daily traffic)	1,022	489	6,981	3,762
Elevation (ft)	6,846	4,769	5,774	6,244
Latitude (degrees)	38.4238460	38.1472426	38.9207000	39.5895546
Longitude (degrees)	111.6551512	110.6596526	111.7760010	111.4733276

Table C.1 Continued

Description	Maintenance Station			
	4421	**4422**	**4423**	**4424**
Salt (yd^3)	368	191	8	78
Redmond Salt (yd^3)	683	490	6	776
Brine (gal)	0	6,000	1,900	900
Wetted Salt (yd^3)	0	0	0	1,165
Magnesium Chloride (gal)	0	0	5,430	11,600
Sand (yd^3)	90	0	2	26
Pre-Mix (yd^3)	348	446	13,185	1,140
Wetted Pre-Mix (yd^3)	0	0	0	1,414
Concrete Surface Area (lane miles)	0.0	0.1	0.0	0.0
Asphalt Surface Area (lane miles)	290.3	276.7	224.7	261.8
Total Pavement Surface Area (lane miles)	290.3	276.8	224.7	261.8
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic)	1,741	1,290	2,465	6,948
Elevation (ft)	4,713	5,323	6,556	4,638
Latitude (degrees)	37.2783766	37.5253586	37.9812266	38.6764446
Longitude (degrees)	109.6221314	110.1110232	109.3760378	109.5619812

Table C.1 Continued

Description	Maintenance Station 4431	4432	4433	4434
Salt (yd^3)	0	14	887	1,667
Redmond Salt (yd^3)	0	167	1,194	1,866
Brine (gal)	0	524	0	7,918
Wetted Salt (yd^3)	0	72	0	45
Magnesium Chloride (gal)	67,849	3,806	0	67,545
Sand (yd^3)	0	18	10	103
Pre-Mix (yd^3)	6,849	3,888	9,978	2,820
Wetted Pre-Mix (yd^3)	723	28	0	215
Concrete Surface Area (lane miles)	0.0	0.0	0.0	0.0
Asphalt Surface Area (lane miles)	225.6	277.5	221.3	222.7
Total Pavement Surface Area (lane miles)	225.6	277.5	221.3	222.7
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic)	6,183	4,499	4,877	7,395
Elevation (ft)	4,621	4,960	6,214	5,546
Latitude (degrees)	38.9406002	38.8987922	39.3461818	39.4661238
Longitude (degrees)	109.5573120	110.3506284	111.0280038	110.5518494

Table C.1 Continued

Description	Maintenance Station			
	4435	4436	4521	4522
Salt (yd^3)	725	116	0	0
Redmond Salt (yd^3)	858	698	20	0
Brine (gal)	22,396	325	0	0
Wetted Salt (yd^3)	75	0	0	0
Magnesium Chloride (gal)	28,194	0	0	0
Sand (yd^3)	250	3	0	0
Pre-Mix (yd^3)	26,009	11,462	536	4,013
Wetted Pre-Mix (yd^3)	605	0	0	0
Concrete Surface Area (lane miles)	0.0	0.0	0.0	0.0
Asphalt Surface Area (lane miles)	173.0	228.1	177.9	220.5
Total Pavement Surface Area (lane miles)	173.0	228.1	177.9	220.5
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic)	5,643	4,455	38,212	11,731
Elevation (ft)	7,334	6,354	3,162	4,105
Latitude (degrees)	39.8022576	38.9080664	37.1493466	37.2455562
Longitude (degrees)	111.0304412	111.0068978	113.5193940	113.2105408

Table C.1 Continued

Description	Maintenance Station			
	4523	**4524**	**4526**	**4527**
Salt (yd^3)	0	885	373	254
Redmond Salt (yd^3)	0	1,380	230	176
Brine (gal)	0	215,856	5,545	34,510
Wetted Salt (yd^3)	0	50	16	714
Magnesium Chloride (gal)	0	11,750	2,330	0
Sand (yd^3)	0	490	2,566	9
Pre-Mix (yd^3)	9,622	15,577	71,436	19,100
Wetted Pre-Mix (yd^3)	0	380	659	3,967
Concrete Surface Area (lane miles)	0.0	0.0	0.0	28.7
Asphalt Surface Area (lane miles)	160.8	216.9	187.1	196.1
Total Pavement Surface Area (lane miles)	160.8	216.9	187.1	224.8
Concrete Proportion	0.000	0.000	0.000	0.128
Traffic (annual average daily traffic)	2,479	16,086	10,395	7,482
Elevation (ft)	5,284	5,624	6,524	6,383
Latitude (degrees)	37.5925374	37.7230984	37.8687028	38.2536372
Longitude (degrees)	113.6697692	113.0888672	112.8032226	112.6182406

Table C.1 Continued

Description	Maintenance Station			
	4531	4532	4534	4535
Salt (yd^3)	14	18	434	596
Redmond Salt (yd^3)	347	72	923	225
Brine (gal)	0	173,450	0	90,982
Wetted Salt (yd^3)	0	613	0	76
Magnesium Chloride (gal)	0	2,434	0	0
Sand (yd^3)	0	54	10	361
Pre-Mix (yd^3)	7,156	21,515	16,521	10,081
Wetted Pre-Mix (yd^3)	0	16,576	0	1,136
Concrete Surface Area (lane miles)	0.0	5.8	0.0	0.0
Asphalt Surface Area (lane miles)	216.4	127.9	173.8	303.6
Total Pavement Surface Area (lane miles)	216.4	133.7	173.8	303.6
Concrete Proportion	0.000	0.043	0.000	0.000
Traffic (annual average daily traffic)	1,022	11,454	8,550	1,507
Elevation (ft)	5,384	6,116	4,855	4,706
Latitude (degrees)	38.4886478	38.6013744	38.9988280	39.2988892
Longitude (degrees)	113.2520140	112.5872040	112.3868408	112.7114866

Table C.1 Continued

Description	Maintenance Station
	4536
Salt (yd^3)	48
Redmond Salt (yd^3)	16
Brine (gal)	6,961
Wetted Salt (yd^3)	106
Magnesium Chloride (gal)	0
Sand (yd^3)	0
Pre-Mix (yd^3)	20,627
Wetted Pre-Mix (yd^3)	682
Concrete Surface Area (lane miles)	18.9
Asphalt Surface Area (lane miles)	68.9
Total Pavement Surface Area (lane miles)	87.8
Concrete Proportion	0.215
Traffic (annual average daily traffic)	8,335
Elevation (ft)	5,323
Latitude (degrees)	39.1585908
Longitude (degrees)	112.2210844

APPENDIX D. DATA USED IN STATISTICAL ANALYSIS

The data set normalized for statistical analysis in this research is presented in Table D.1.

Table D.1 Data Used in Statistical Analysis

Description	Maintenance Station			
	1421	**1422**	**1423**	**1424**
Salt ($\ln(yd^3$/lane-mile))	3.576	3.935	3.438	4.169
Redmond Salt ($\ln(yd^3$/lane-mile))	0.238	0.000	0.942	0.495
Brine ($\ln(yd^3$/lane-mile))	0.118	0.425	0.550	0.797
Wetted Salt ($\ln(yd^3$/lane-mile))	0.735	2.124	2.122	2.959
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.000	0.155	0.243	0.262
Sand ($\ln(yd^3$/lane-mile))	1.579	1.953	0.805	1.715
Pre-Mix ($\ln(yd^3$/lane-mile))	0.084	0.584	2.347	1.008
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.000	0.164	0.560	0.000
Total Deicer ($\ln(yd^3$/lane-mile))	3.717	4.193	3.961	4.515
Concrete Proportion	0.000	0.177	0.120	0.496
Traffic (annual average daily traffic per lane mile)	99.0	170.7	89.8	269.7
Elevation (1000 ft)	4.340	4.342	4.400	4.333
Latitude (degrees)	41.1948300	41.2352464	41.4853232	41.0415286

Table D.1 Continued

Description	Maintenance Station			
	1425	1426	1427	1431
Salt (ln(yd^3/lane-mile))	2.807	3.914	4.446	0.270
Redmond Salt (ln(yd^3/lane-mile))	1.488	0.936	0.582	0.042
Brine (ln(yd^3/lane-mile))	0.104	0.000	1.956	0.090
Wetted Salt (ln(yd^3/lane-mile))	0.000	0.086	0.008	0.000
Magnesium Chloride (ln(yd^3/lane-mile))	0.203	0.106	0.053	0.063
Sand (ln(yd^3/lane-mile))	0.202	1.790	2.142	0.028
Pre-Mix (ln(yd^3/lane-mile))	4.915	4.221	0.032	3.175
Wetted Pre-Mix (ln(yd^3/lane-mile))	0.000	0.000	0.000	0.028
Total Deicer (ln(yd^3/lane-mile))	5.049	4.820	4.602	3.198
Concrete Proportion	0.000	0.266	0.196	0.125
Traffic (annual average daily traffic per lane mile)	40.4	68.5	588.7	17.9
Elevation (1000 ft)	5.243	5.578	4.366	4.747
Latitude (degrees)	41.2443108	40.9908166	40.8808550	41.7376920

Table D.1 Continued

Description	Maintenance Station			
	1432	1433	1435	1436
Salt (ln(yd^3/lane-mile))	1.097	2.080	3.906	2.473
Redmond Salt (ln(yd^3/lane-mile))	0.000	0.445	0.691	0.921
Brine (ln(yd^3/lane-mile))	0.787	0.344	0.119	0.013
Wetted Salt (ln(yd^3/lane-mile))	1.341	0.454	0.000	0.036
Magnesium Chloride (ln(yd^3/lane-mile))	0.203	0.231	0.156	0.147
Sand (ln(yd^3/lane-mile))	0.042	0.000	0.414	0.465
Pre-Mix (ln(yd^3/lane-mile))	3.368	3.779	3.961	3.475
Wetted Pre-Mix (ln(yd^3/lane-mile))	3.056	1.804	0.041	0.857
Total Deicer (ln(yd^3/lane-mile))	4.017	4.055	4.635	3.846
Concrete Proportion	0.374	0.428	0.000	0.000
Traffic (annual average daily traffic per lane mile)	33.7	62.4	63.2	75.0
Elevation (1000 ft)	4.423	4.608	4.665	4.826
Latitude (degrees)	41.6910616	41.7705700	41.6793988	41.8553714

Table D.1 Continued

Description	Maintenance Station			
	1437	2421	2422	2423
Salt ($ln(yd^3/lane\text{-}mile)$)	0.000	3.411	3.825	4.501
Redmond Salt ($ln(yd^3/lane\text{-}mile)$)	0.000	0.000	1.275	0.504
Brine ($ln(yd^3/lane\text{-}mile)$)	0.024	0.126	0.000	0.000
Wetted Salt ($ln(yd^3/lane\text{-}mile)$)	0.029	2.125	0.000	0.000
Magnesium Chloride ($ln(yd^3/lane\text{-}mile)$)	0.078	0.008	0.000	0.000
Sand ($ln(yd^3/lane\text{-}mile)$)	0.000	0.122	0.958	0.936
Pre-Mix ($ln(yd^3/lane\text{-}mile)$)	3.782	0.000	0.021	0.045
Wetted Pre-Mix ($ln(yd^3/lane\text{-}mile)$)	0.481	0.026	0.000	0.000
Total Deicer ($ln(yd^3/lane\text{-}mile)$)	3.799	3.636	3.913	4.525
Concrete Proportion	0.054	0.000	0.123	0.000
Traffic (annual average daily traffic per lane mile)	7.5	25.3	84.5	39.4
Elevation (1000 ft)	6.598	4.320	4.492	5.146
Latitude (degrees)	41.6936680	40.7376832	40.6029818	40.3223328

Table D.1 Continued

Description	Maintenance Station			
	2424	2425	2427	2430
Salt ($\ln(yd^3$/lane-mile))	3.632	4.234	4.295	4.342
Redmond Salt ($\ln(yd^3$/lane-mile))	1.168	1.932	0.978	0.203
Brine ($\ln(yd^3$/lane-mile))	1.575	2.099	1.510	2.654
Wetted Salt ($\ln(yd^3$/lane-mile))	3.934	0.000	1.062	2.977
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.147	0.000	0.000	0.073
Sand ($\ln(yd^3$/lane-mile))	0.819	3.724	0.986	2.943
Pre-Mix ($\ln(yd^3$/lane-mile))	0.172	2.161	0.016	2.136
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.503	3.631	3.494	0.656
Total Deicer ($\ln(yd^3$/lane-mile))	4.566	5.117	4.737	4.908
Concrete Proportion	0.518	0.328	0.590	0.708
Traffic (annual average daily traffic per lane mile)	219.6	461.3	257.4	511.1
Elevation (1000 ft)	4.236	4.319	4.551	4.265
Latitude (degrees)	40.7479808	40.7714148	40.5202172	40.7572058

Table D.1 Continued

Description	Maintenance Station			
	2431	2432	2433	2434
Salt ($\ln(yd^3$/lane-mile))	4.736	4.571	5.070	2.911
Redmond Salt ($\ln(yd^3$/lane-mile))	0.580	2.061	5.952	0.000
Brine ($\ln(yd^3$/lane-mile))	0.545	2.418	2.226	3.108
Wetted Salt ($\ln(yd^3$/lane-mile))	2.245	0.568	0.311	5.301
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.037	0.000	0.000	0.000
Sand ($\ln(yd^3$/lane-mile))	0.939	2.041	1.413	1.020
Pre-Mix ($\ln(yd^3$/lane-mile))	1.161	0.000	1.572	0.000
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.157	3.771	0.242	1.741
Total Deicer ($\ln(yd^3$/lane-mile))	4.851	5.098	6.325	5.504
Concrete Proportion	0.318	0.525	0.348	0.139
Traffic (annual average daily traffic per lane mile)	187.4	689.4	267.3	392.3
Elevation (1000 ft)	4.676	4.306	4.549	5.467
Latitude (degrees)	40.6317568	40.6525598	40.6650386	40.7450052

Table D.1 Continued

Description	Maintenance Station			
	2435	**2436**	**2437**	**2438**
Salt ($\ln(yd^3$/lane-mile))	6.410	5.542	5.377	5.152
Redmond Salt ($\ln(yd^3$/lane-mile))	2.318	1.822	1.295	2.459
Brine ($\ln(yd^3$/lane-mile))	2.955	0.105	2.158	0.000
Wetted Salt ($\ln(yd^3$/lane-mile))	2.852	0.000	1.222	0.000
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.140	0.046	0.137	0.000
Sand ($\ln(yd^3$/lane-mile))	3.129	1.697	1.583	4.646
Pre-Mix ($\ln(yd^3$/lane-mile))	0.000	0.268	1.563	0.000
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.000	0.000	0.113	0.000
Total Deicer ($\ln(yd^3$/lane-mile))	6.512	5.581	5.468	5.658
Concrete Proportion	0.171	0.000	0.000	0.000
Traffic (annual average daily traffic per lane mile)	246.5	113.8	17.5	76.9
Elevation (1000 ft)	7.018	5.825	7.622	5.845
Latitude (degrees)	40.6978254	40.8727866	40.6538238	41.0474324

Table D.1 Continued

Description	Maintenance Station 3421	3422	3423	3424
Salt ($ln(yd^3$/lane-mile))	0.019	4.784	4.423	4.398
Redmond Salt ($ln(yd^3$/lane-mile))	2.628	3.156	3.004	3.567
Brine ($ln(yd^3$/lane-mile))	0.000	0.000	0.350	0.000
Wetted Salt ($ln(yd^3$/lane-mile))	0.000	0.744	0.537	0.000
Magnesium Chloride ($ln(yd^3$/lane-mile))	0.000	0.000	0.000	0.000
Sand ($ln(yd^3$/lane-mile))	0.019	1.104	0.366	0.863
Pre-Mix ($ln(yd^3$/lane-mile))	3.651	1.796	2.851	0.820
Wetted Pre-Mix ($ln(yd^3$/lane-mile))	0.000	0.000	0.546	0.000
Total Deicer ($ln(yd^3$/lane-mile))	3.939	5.012	4.797	4.774
Concrete Proportion	0.000	0.303	0.004	0.000
Traffic (annual average daily traffic per lane mile)	6.8	33.6	169.8	127.1
Elevation (1000 ft)	5.305	5.199	4.588	4.699
Latitude (degrees)	39.9159980	39.6681164	40.3902772	40.0443110

Table D.1 Continued

Description	Maintenance Station 3425	3426	3427	3431
Salt ($ln(yd^3$/lane-mile))	5.742	2.213	2.632	0.276
Redmond Salt ($ln(yd^3$/lane-mile))	3.789	3.525	3.637	0.609
Brine ($ln(yd^3$/lane-mile))	0.023	0.000	0.008	0.004
Wetted Salt ($ln(yd^3$/lane-mile))	0.354	0.000	0.000	0.032
Magnesium Chloride ($ln(yd^3$/lane-mile))	0.000	0.000	0.038	0.002
Sand ($ln(yd^3$/lane-mile))	3.010	0.000	0.025	0.071
Pre-Mix ($ln(yd^3$/lane-mile))	1.669	3.283	0.000	4.268
Wetted Pre-Mix ($ln(yd^3$/lane-mile))	0.000	0.044	0.000	0.640
Total Deicer ($ln(yd^3$/lane-mile))	5.937	4.217	3.931	4.298
Concrete Proportion	0.222	0.001	0.060	0.221
Traffic (annual average daily traffic per lane mile)	235.7	88.9	336.6	82.5
Elevation (1000 ft)	5.911	4.591	4.610	6.199
Latitude (degrees)	40.3802766	40.1157300	40.2674602	40.5794706

Table D.1 Continued

Description	Maintenance Station			
	3433	3434	3435	3437
Salt ($\ln(yd^3$/lane-mile))	0.088	0.128	0.705	1.372
Redmond Salt ($\ln(yd^3$/lane-mile))	0.021	0.101	1.829	0.105
Brine ($\ln(yd^3$/lane-mile))	0.000	0.000	0.000	0.064
Wetted Salt ($\ln(yd^3$/lane-mile))	0.000	0.000	0.000	0.000
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.000	0.000	0.000	0.000
Sand ($\ln(yd^3$/lane-mile))	1.260	0.000	0.192	0.230
Pre-Mix ($\ln(yd^3$/lane-mile))	3.706	3.517	3.134	3.150
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.000	0.000	0.000	0.000
Total Deicer ($\ln(yd^3$/lane-mile))	3.769	3.524	3.382	3.285
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic per lane mile)	7.0	18.4	31.5	29.9
Elevation (1000 ft)	6.639	6.334	5.408	5.890
Latitude (degrees)	40.3188554	40.1412196	40.3144660	40.5037490

Table D.1 Continued

Description	Maintenance Station			
	3445	4321	4322	4324
Salt (ln(yd^3/lane-mile))	1.110	0.000	0.000	0.000
Redmond Salt (ln(yd^3/lane-mile))	3.555	0.065	0.000	4.174
Brine (ln(yd^3/lane-mile))	0.143	0.000	0.000	0.000
Wetted Salt (ln(yd^3/lane-mile))	0.000	0.000	0.000	0.219
Magnesium Chloride (ln(yd^3/lane-mile))	0.000	0.000	0.000	0.067
Sand (ln(yd^3/lane-mile))	2.198	0.762	0.000	0.000
Pre-Mix (ln(yd^3/lane-mile))	5.149	2.108	3.095	3.613
Wetted Pre-Mix (ln(yd^3/lane-mile))	0.000	0.000	0.000	0.533
Total Deicer (ln(yd^3/lane-mile))	5.377	2.245	3.095	4.626
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic per lane mile)	35.0	28.1	15.1	7.2
Elevation (1000 ft)	6.973	4.865	6.825	6.748
Latitude (degrees)	40.3180994	37.0821092	37.4218294	37.7888264

Table D.1 Continued

Description	Maintenance Station			
	4325	4326	4327	4328
Salt ($\ln(yd^3$/lane-mile))	0.000	0.000	0.056	0.612
Redmond Salt ($\ln(yd^3$/lane-mile))	0.093	0.000	0.935	0.380
Brine ($\ln(yd^3$/lane-mile))	0.000	0.002	0.108	0.000
Wetted Salt ($\ln(yd^3$/lane-mile))	0.000	0.000	0.000	0.000
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.000	0.000	0.000	0.000
Sand ($\ln(yd^3$/lane-mile))	0.063	0.268	0.000	0.279
Pre-Mix ($\ln(yd^3$/lane-mile))	3.385	3.262	3.295	3.107
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.204	0.000	0.000	0.000
Total Deicer ($\ln(yd^3$/lane-mile))	3.398	3.274	3.356	3.177
Concrete Proportion	0.000	0.000	0.661	0.000
Traffic (annual average daily traffic per lane mile)	28.6	7.4	17.5	70.5
Elevation (1000 ft)	6.953	6.198	5.869	5.340
Latitude (degrees)	37.8635112	38.2772736	38.6620680	39.2437940

Table D.1 Continued

Description	Maintenance Station			
	4331	4332	4333	4334
Salt ($\ln(yd^3$/lane-mile))	0.029	0.000	0.449	0.163
Redmond Salt ($\ln(yd^3$/lane-mile))	0.000	0.000	1.477	0.639
Brine ($\ln(yd^3$/lane-mile))	0.056	0.000	0.000	0.000
Wetted Salt ($\ln(yd^3$/lane-mile))	0.000	0.000	1.716	0.000
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.070	0.000	0.000	0.000
Sand ($\ln(yd^3$/lane-mile))	0.000	0.000	0.000	0.042
Pre-Mix ($\ln(yd^3$/lane-mile))	3.115	1.119	3.858	3.722
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.000	0.000	2.646	0.021
Total Deicer ($\ln(yd^3$/lane-mile))	3.122	1.119	4.234	3.750
Concrete Proportion	0.000	0.000	0.006	0.000
Traffic (annual average daily traffic per lane mile)	3.8	2.0	22.7	20.1
Elevation (1000 ft)	6.846	4.769	5.774	6.244
Latitude (degrees)	38.4238460	38.1472426	38.9207000	39.5895546

Table D.1 Continued

Description	Maintenance Station			
	4421	4422	4423	4424
Salt ($\ln(yd^3$/lane-mile))	0.819	0.525	0.035	0.261
Redmond Salt ($\ln(yd^3$/lane-mile))	1.210	1.019	0.026	1.377
Brine ($\ln(yd^3$/lane-mile))	0.000	0.025	0.010	0.004
Wetted Salt ($\ln(yd^3$/lane-mile))	0.000	0.000	0.000	1.696
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.000	0.000	0.035	0.064
Sand ($\ln(yd^3$/lane-mile))	0.270	0.000	0.009	0.095
Pre-Mix ($\ln(yd^3$/lane-mile))	0.470	0.591	3.413	1.156
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.000	0.000	0.000	1.308
Total Deicer ($\ln(yd^3$/lane-mile))	1.710	1.457	3.416	2.622
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic per lane mile)	6.0	4.7	11.0	26.5
Elevation (1000 ft)	4.713	5.323	6.556	4.638
Latitude (degrees)	37.2783766	37.5253586	37.9812266	38.6764446

Table D.1 Continued

Description	Maintenance Station			
	4431	**4432**	**4433**	**4434**
Salt ($\ln(yd^3$/lane-mile))	0.000	0.049	1.611	2.138
Redmond Salt ($\ln(yd^3$/lane-mile))	0.000	0.471	1.855	2.239
Brine ($\ln(yd^3$/lane-mile))	0.000	0.002	0.000	0.041
Wetted Salt ($\ln(yd^3$/lane-mile))	0.000	0.231	0.000	0.184
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.370	0.020	0.000	0.373
Sand ($\ln(yd^3$/lane-mile))	0.000	0.063	0.044	0.380
Pre-Mix ($\ln(yd^3$/lane-mile))	2.784	2.080	3.159	1.992
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.956	0.049	0.000	0.394
Total Deicer ($\ln(yd^3$/lane-mile))	2.903	2.203	3.496	3.212
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic per lane mile)	27.4	16.2	22.0	33.2
Elevation (1000 ft)	4.621	4.960	6.214	5.546
Latitude (degrees)	38.9406002	38.8987922	39.3461818	39.4661238

Table D.1 Continued

Description	Maintenance Station 4435	4436	4521	4522
Salt ($ln(yd^3$/lane-mile))	1.647	0.411	0.000	0.000
Redmond Salt ($ln(yd^3$/lane-mile))	1.785	1.401	0.107	0.000
Brine ($ln(yd^3$/lane-mile))	0.143	0.002	0.000	0.000
Wetted Salt ($ln(yd^3$/lane-mile))	0.360	0.000	0.000	0.000
Magnesium Chloride ($ln(yd^3$/lane-mile))	0.217	0.000	0.000	0.000
Sand ($ln(yd^3$/lane-mile))	0.894	0.013	0.000	0.000
Pre-Mix ($ln(yd^3$/lane-mile))	4.333	3.263	0.919	2.312
Wetted Pre-Mix ($ln(yd^3$/lane-mile))	1.011	0.000	0.000	0.000
Total Deicer ($ln(yd^3$/lane-mile))	4.493	3.391	0.963	2.312
Concrete Proportion	0.000	0.000	0.000	0.000
Traffic (annual average daily traffic per lane mile)	32.6	19.5	214.8	53.2
Elevation (1000 ft)	7.334	6.354	3.162	4.105
Latitude (degrees)	39.8022576	38.9080664	37.1493466	37.2455562

Table D.1 Continued

Description	Maintenance Station			
	4523	4524	4526	4527
Salt ($\ln(yd^3$/lane-mile))	0.000	1.625	1.096	0.756
Redmond Salt ($\ln(yd^3$/lane-mile))	0.000	1.996	0.802	0.578
Brine ($\ln(yd^3$/lane-mile))	0.000	0.779	0.035	0.167
Wetted Salt ($\ln(yd^3$/lane-mile))	0.000	0.207	0.082	1.429
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.000	0.078	0.018	0.000
Sand ($\ln(yd^3$/lane-mile))	0.000	1.181	2.689	0.039
Pre-Mix ($\ln(yd^3$/lane-mile))	3.431	3.608	5.257	3.772
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.000	0.629	1.015	2.285
Total Deicer ($\ln(yd^3$/lane-mile))	3.431	3.951	5.350	4.054
Concrete Proportion	0.000	0.000	0.000	0.128
Traffic (annual average daily traffic per lane mile)	15.4	74.2	55.5	33.3
Elevation (1000 ft)	5.284	5.624	6.524	6.383
Latitude (degrees)	37.5925374	37.7230984	37.8687028	38.2536372

Table D.1 Continued

Description	Maintenance Station			
	4531	**4532**	**4534**	**4535**
Salt ($\ln(yd^3$/lane-mile))	0.063	0.126	1.252	1.086
Redmond Salt ($\ln(yd^3$/lane-mile))	0.957	0.431	1.842	0.555
Brine ($\ln(yd^3$/lane-mile))	0.000	0.931	0.000	0.304
Wetted Salt ($\ln(yd^3$/lane-mile))	0.000	1.720	0.000	0.223
Magnesium Chloride ($\ln(yd^3$/lane-mile))	0.000	0.027	0.000	0.000
Sand ($\ln(yd^3$/lane-mile))	0.000	0.339	0.056	0.784
Pre-Mix ($\ln(yd^3$/lane-mile))	2.864	4.400	3.882	2.868
Wetted Pre-Mix ($\ln(yd^3$/lane-mile))	0.000	4.143	0.000	1.055
Total Deicer ($\ln(yd^3$/lane-mile))	2.955	5.015	4.032	3.177
Concrete Proportion	0.000	0.043	0.000	0.000
Traffic (annual average daily traffic per lane mile)	4.7	85.6	49.2	5.0
Elevation (1000 ft)	5.384	6.116	4.855	4.706
Latitude (degrees)	38.4886478	38.6013744	38.9988280	39.2988892

Table D.1 Continued

Description	Maintenance Station
	4536
Salt (ln(yd^3/lane-mile))	0.436
Redmond Salt (ln(yd^3/lane-mile))	0.167
Brine (ln(yd^3/lane-mile))	0.090
Wetted Salt (ln(yd^3/lane-mile))	0.792
Magnesium Chloride (ln(yd^3/lane-mile))	0.000
Sand (ln(yd^3/lane-mile))	0.000
Pre-Mix (ln(yd^3/lane-mile))	4.774
Wetted Pre-Mix (ln(yd^3/lane-mile))	1.586
Total Deicer (ln(yd^3/lane-mile))	4.823
Concrete Proportion	0.215
Traffic (annual average daily traffic per lane mile)	94.9
Elevation (1000 ft)	5.323
Latitude (degrees)	39.1585908