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Selection of Effective and Efficient Snow Removal and Ice Control Technologies for Cold-Region Bridges

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Abstract

In cold regions, snow and ice pose serious hazards to motorists. In order to minimize their detrimental effects caused by snow and ice on roadways, snow removal and ice control measures are necessary. So far, there is no single solution for snow and ice control on roadways. The aim of this work is to provide a procedure of selection of bridge deicing in cold regions. A comprehensive literature review of deicing and anti-icing techniques is first presented. Factors affecting the method choice are discussed. Finally, a case study of demonstrating the selection of an appropriate method of ice control for bridge deicing is performed.

1. Introduction

In the northern United States, Canada, and many northern European countries, snow and ice pose serious hazards to motorists. Potential traffic disruptions caused by ice and snow are challenges faced by transportation agencies. Although there is considerable literature related to snow removal and ice control measures [1-6], no single solution is available. Many factors affect the selection of a specific deicing project, for example, geographical location, intensity of precipitation, and cost. A comprehensive literature review on the available deicing and anti-icing technologies in cold regions is critically needed.

In general, there are two distinct snow and ice control strategies that break or weaken the bonds that hold ice and snow to a road surface: deicing and anti-icing [7]. They differ in their fundamental objectives. Deicing operations are performed to break the bond of snow and ice that are already bonded to road. Anti-icing operations are conducted using timely applications of a freezing-point depressant to prevent the formation or development of bonded snow and ice, so they can be easily removed. Since the primary difference between deicing and anti-icing is the time of operation, for simplicity, we only choose the term deicing in the following text.

Deicing operations commonly start after snow has accumulated and bonded to the pavement surface. In contrast, anti-icing is applied before snow events and provides a means of maintaining pavement in the best possible condition during a winter storm. Thus, anti-icing has the potential to provide the benefit of increased traffic safety. To achieve this benefit, however, a systematic approach has to be adopted. Such an approach requires good judgment in making decisions in a timely manner [7].

The objective of this study is to provide a comprehensive methodology for deicing and anti-icing practices for cold-region bridges. Section 2 presents a literature investigation of chemical methods, with an analysis of approximate cost per freezing event. Section 3 describes a literature investigation of thermal methods. Section 4 reviews other innovative anti-icing methods. Section 5 analyzes key factors affecting the selection of various methods. Section 6 demonstrates a methodology developed for a case study involving the proposed Knik Arm Bridge.

2. Chemical Methods

2. 1 Chemical Methods

This section discusses the chemical and physical properties of chemicals used by ice control technologies. Each winter, large amounts of solid and liquid chemicals are applied to keep pavement surfaces clear of ice and snow. The widely used chemicals include sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$), potassium acetate (KAc), and calcium magnesium acetate (CMA).

These chemicals melt ice and snow by lowering the freezing point of the snow-salt mixture. Figure 1 summarizes eutectic temperatures and concentrations of the chemicals. The eutectic temperature is the lowest freezing point attainable for a given product and occurs at the eutectic concentration. The freezing point is the temperature at which a given solution will freeze, and it depends on chemical concentration.

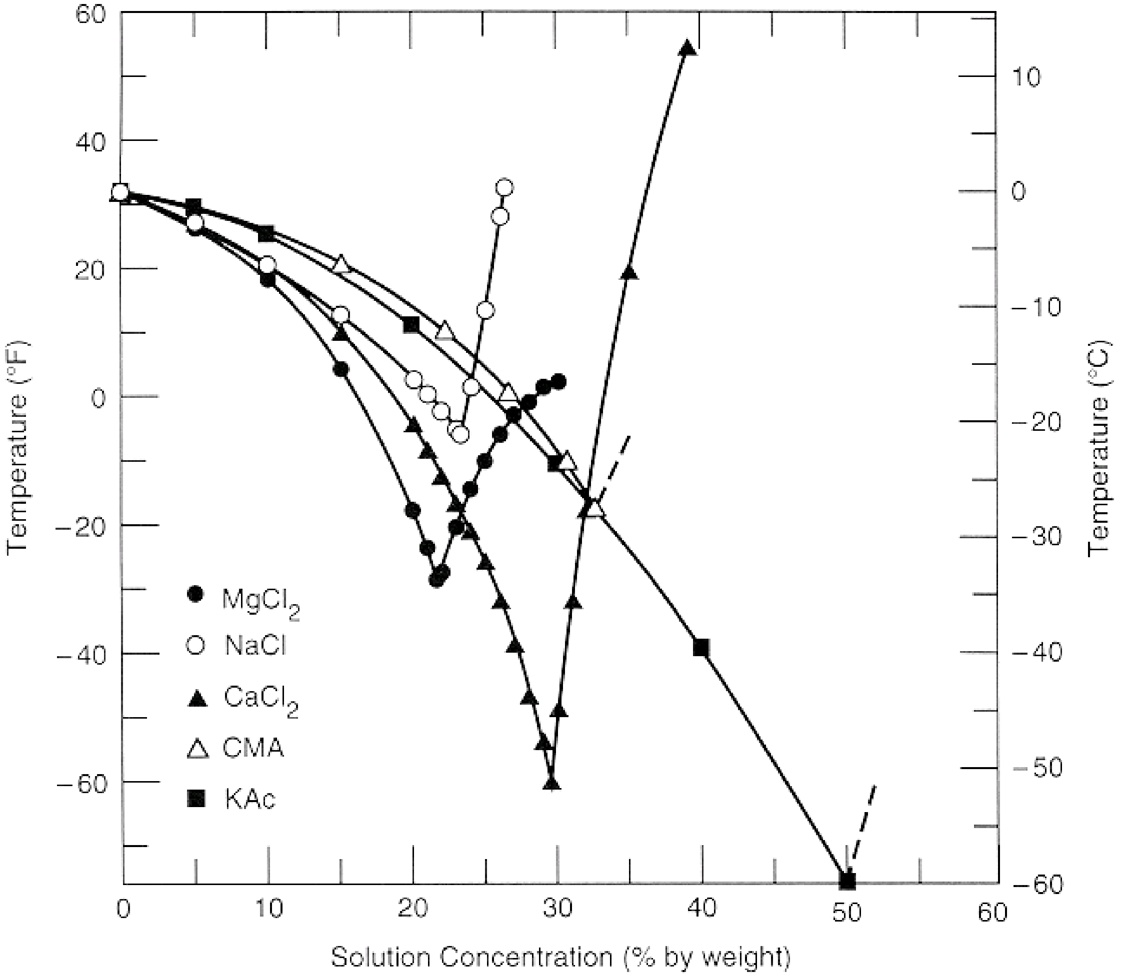

Fig. 1. Eutectic temperature and eutectic concentration of five chemicals [2, 7, 8].

Sodium chloride (NaCl):

Sodium chloride is also known as rock salt. So far, it is the least expensive and most widely used deicing chemical. Use of NaCl has declined recently because other chemicals have proven more effective and less detrimental to the environment. NaCl can accelerate corrosion rates of automobiles, steel reinforced concrete, and the steel structures of bridges. The addition of organic anti-corrosion agents has been moderately effective in reducing the rate of accelerated corrosion. There are also reports that brine seepage into road cracks can cause differential frost heaving [9]. The operating temperature of NaCl is higher than most chemicals, with a eutectic temperature of -21°C at a concentration of 23% [7]. A pre-wetting fluid is often used when applying solid rock salt to roadways, which improves initial adherence and prevents the salt from bouncing off the pavement.

Calcium chloride ($CaCl_2$):

Calcium chloride is available as an aqueous mixture or anhydrous solid. The aqueous mixture is commonly referred to as liquid calcium. It is primarily used for dust control and as a pre-wetting agent for use with rock salt (sodium chloride). A 2003 laboratory study by the Maine Department of Transportation (DOT) concluded that the addition of liquid calcium to rock salt did not significantly increase deicing rates except in the first 5–10 minutes after application, and therefore, the added cost was not justified [10]. Although more expensive than rock salt, liquid calcium is relatively inexpensive; it is usually shipped in bulk truck tanks or railcars or by barge.

Magnesium chloride ($MgCl_2$):

Magnesium chloride is similar to sodium chloride in their chemical properties. Magnesium may react with cement paste in concrete and weaken its structure. In 2004, the Maine DOT examined a commercial liquid $MgCl_2$ product that contains an organic anti-corrosion agent. It proved less corrosive to metals and had less impact on plants and water than any other salt [9]. Plow operators reported that the product performed better than both liquid calcium and $CaCl_2$ in both deicing and anti-icing applications [9].

Potassium acetate (KAc):

Compared with NaCl, potassium acetate is less corrosive and can be applied to corrosion-sensitive structures like bridges and concrete surfaces. When it degrades, KAc releases potassium and acetate. The acetate breaks down further, producing carbon dioxide and water. KAc is compatible with stainless steel, aluminum, and cast iron; it is also compatible with rubber and PVC (polyvinyl chloride). The eutectic temperature of KAc is about -60°C (-76°F) at a concentration of 49% [9]. Although both KAc and NaCl are preferable to road salt, they are much more expensive, which limits widespread adoption of their use.

Calcium magnesium acetate (CMA):

Calcium magnesium acetate is a patented chemical formulation from dolomitic lime and acetic acid. It was first identified as a low-corrosion environmental alternative to road salt by the U.S. Federal Highway Administration in the late 1970s [11]. The operating temperature of CMA is lower than chloride chemicals with a eutectic temperature of -28°C at a concentration of 32.5% [9]. CMA is generally used in its granular form and spread on surfaces like other deicers. CMA exhibits very low corrosion rates on metals found in bridges, roadways, and parking garages, and in other steel and concrete systems. Commonly described as being about as corrosive as tap water, CMA is often used as the corrosion standard by which other deicers are judged [11].

2. 2 Applicability and Cost Analysis of Various Chemical Methods

The applicability and cost of various chemicals depend on several factors, including eutectic temperature, availability of raw materials, and process methods. For example, NaCl has been used as an ice control chemical on roads since 1900s. It is produced primarily by three processes: rock salt mining, evaporation of seawater, and drying the solution of deep underground deposits. CMA is produced by reacting acetic acid with dolomitic lime. Whereas dolomitic lime is abundant and inexpensive, acetic acid is far more costly. Currently, the most economical method of producing acetic acid is by using natural gas as a feedstock. After spending several years investing in alternative processes for producing CMA, the Federal Highway Administration (FHWA) and most states now rely on industry for further development. A summary of the cost of these chemicals is given in Table 1.

Table 1. Cost of deicing chemicals and their temperature range and application rate [1, 6, 12, 13].

Deicing Chemical	Temperature Range	Application Rate	Approximate Cost in Volume	Approximate Cost in Area
Sodium chloride (NaCl)	-10°C to 1°C (14°F to 34°F)	13 to 68 g/m^2 (170 to 890 lb/12 ft lane-mile)	\$29/m^3 (\$26/ton)	\$0.0003/m^2
Calcium chloride ($CaCl_2$)	-25°C (-13°F)	Use along with sodium chloride in U.S.	\$294/m^3 (\$267/ton)	\$0.03/m^2
Salt mixed with calcium chloride (NaCl and $CaCl_2$)	-17°C to 0°C (0°F to 32°F)	21–50 l/m^3 salt (5 to 12 gal/ton)	\$108/m^3 (\$98/ton)	\$0.01/m^2
Magnesium chloride ($MgCl_2$)	-15°C (5°F)	8 to 11 g/m^2 (100 to 150 lb/12 ft lane-mile)	Not available	\$0.0002/m^2
Calcium magnesium acetate (CMA)	-5°C to 0°C (23°F to 32°F)	15 to 39 g/m^2 (200 to 500 lb/12 ft lane-mile)	\$738/m^3 (\$670/ton)	\$0.004/m^2
Potassium acetate (KAc)	50% to 35% concentration solution freezes at -60°C to -30°C (-76°F to -22°F)	0.9 to 9.1 gal/1000 ft^2	Not available	Not available

3. Thermal Methods

3.1 Thermal Deicing Methods

This section introduces thermal methods for deicing purposes. Interest in thermal methods for deicing has grown as concerns increase over the environmental impact of chemicals on soil and groundwater, and the potential corrosion of bridge deck structures. Thermal methods, or pavement heating methods, offer an alternative to the use of chemical agents [14]. Several methods for pavement heating have been explored, and they are discussed below.

Electrically conductive concrete:

Electrically conductive concrete is a type of composite made up of steel fiber, steel shavings, and regular concrete. About 15% of the conductive material by volume is mixed with concrete to make this compound [6]. The metallic components provide higher electrical conductivity. When electrical power is applied to this conductive concrete, heat is generated by the electrical resistance of the metallic particles and steel fibers. In one of the designs, conductive concrete 2 in. thick is overlaid on a 6 in. thick regular concrete deck [6]. A thermal insulation layer between the conductive concrete and the regular concrete deck is provided to minimize heat loss to the bridge deck. Heat is directed into the ice layer above the conductive concrete, causing the ice to melt.

Electrical resistive heating:

Electrical heating wires can be embedded below the surface of the pavement in the wheel track regions of the lanes. Several strands of wire run parallel along the wheel track. Surface-mounted sensors or cameras that detect frost or snow on the pavement activate these wires, which help to melt snow and ice and prevent the formation of black ice. The Ladd Canyon Heating Project by the Oregon DOT is testing this method at a one-mile section on Interstate Highway I-84 [15].

In Japan, at locations where pavement freezing poses a significant hazard to drivers, such as at sharp curves, the pavement is heated using electrical resistive wiring embedded in the road. This technique has also been used in urban areas for crosswalks and sidewalks [5].

Geothermal heat pumps:

In geothermal heat pump systems, heat is extracted from the ground by a ground-loop heat exchanger. The heat is transferred to a propylene glycol mixture in a series of heat exchangers, which is then circulated throughout the bridge deck for deicing purposes. Such a system for deicing a bridge deck is being tested in Oklahoma [16]. In this deck, hydronic fluid is circulated via polyethylene tubes embedded in the bridge deck in a serpentine fashion. The tube size is 18 mm in diameter, spaced 300 mm apart. The coiled tubes are placed 75 mm below the road surface. The deck thickness is 200 mm. For a bridge deck of 215 m × 12 m, being heated on the west-bound side, 16 heat pumps, each 106 kW, are required [16].

Infrared heating:

Infrared heaters can be mounted on a truck or on bridge side structures, with their beams directed toward the snow and ice on the bridge deck to melt it. The infrared heating system has been applied to aircraft deicing [14].

Microwave and radio frequency power:

Other power sources under consideration are microwave and radio frequencies (RF). Similar to a microwave oven, microwave beams can be focused from a truck-mounted system [17] or from bridge structures onto an icy surface to heat and melt it. Likewise, RF resonators may be vehicle-mounted or mounted to bridge side structures and excited to generate enough heat to be absorbed by ice and snow, resulting in melting [6].

Solar and wind power:

Photovoltaic cells may be considered for augmenting electrical power on a bridge in climates where there is sufficient sunlight in winter. At locations where wind speed prevails over a bridge, it is possible to run small-scale wind turbines to generate electricity, which can be used to supplement the electrical energy needed for deicing the bridge deck.

3.2 Cost Analysis of Various Thermal Methods

The estimated cost of primary thermal methods is given in Table 2. Capital and operating costs strongly depend on the size of the area where thermal methods are applied. In general, the cost of thermal methods is substantially higher than that of chemical methods.

Table 2. Cost estimates for various heating systems [6, 15, 16, 18].

Heating	Approximate Capital Cost	Power Consumption	Operating Cost
Infrared Heat Lamp	$96/m^2$ ($8.9/ft^2)	75 W/m^2 (7 W/ft^2)	Not available
Electric Heating Cable	$54/m^2 ($5/ft^2)	323–430 W/m^2 (30–40 W/ft^2)	$4.8/m^2 ($0.45/ft^2)
Hot Water	$161/m^2 ($15/ft^2)	473 W/m^2 (44 W/ft^2)	$250/Storm, 3-inch snow
Heated Gas	$378/m^2 ($35/ft^2)	Not available	$2.1/m^2 ($0.2/ft^2)
Conductive Concrete Overlay	$48/m^2 ($4.5/ft^2)	516 W/m^2 (48 W/ft^2)	$5.4/m^2 ($0.5 ft^2)

4. Additional Snow and Ice Control Methods

In addition to the chemical and thermal techniques discussed in Sections 2 and 3, many additional strategies have been used in snow and ice control operations. The most relevant techniques are summarized below.

Fixed Automated Spray Technology (FAST):

The Fixed Automated Spray Technology system uses active and passive sensors embedded in the road surface to predict surface temperature and activate the spray system. The system continuously monitors conditions on the structure, based on the detection of critical threshold parameters, and sprays the chemical just in advance of icing conditions. Road sensors can be either passive or active. Passive sensors are tuned for the type of deicing chemical used in order to determine the proper freezing-point depression. Active sensors use a peltier junction and can accurately measure the freezing point independent of the type of chemicals being used. As of 2003, 23 states either have FAST systems or are planning to install them [19].

Road Weather Information System (RWIS):

Road Weather Information Systems are small weather stations that provide specialized information on road surface conditions in addition to traditional weather data such as temperature, wind speed, and humidity. They monitor the presence of surface moisture, determining when deicing needs to take place. RWIS is instrumental for effective anti-icing and usually is integrated with the FAST system. There are three primary components of an RWIS, each contributing to the cost of the system: the pavement and air sensors, the electrical and computer hardware and software, and the information transmission lines or corresponding wireless hardware.

Porous overlay:

A modified pavement surface can be used in conjunction with other anti-icing and deicing techniques. The addition of a porous overlay, comprised of aggregate and epoxy, has the potential to store deicing chemicals that would otherwise drain or be splashed off by passing automobiles. A commercial porous overlay [20] uses a special aggregate that acts together with an adhesive in a sponge-like manner such that when an anti-icing liquid is applied to the surface, it is retained for a significant portion of time, typically several days, remaining effective as an anti-icing chemical during that time. Anecdotal evidence and studies indicate that porous overlay has decreased accident rates and lowered road maintenance costs at most installations [20]. Maintenance costs are reduced because deicing chemicals can be applied during regular working hours instead of on an on-call basis [20].

5. Geographic, Economical, and Environmental Factors

To select from available deicing techniques, information related to location—for example, geographic, economical, and environmental factors—should also be considered. This section discusses these factors.

5.1 Geographic Factor

Geographic location is probably the most important factor affecting the amount and frequency of precipitation. Meteorological data, such as snow or icing events, are typically recorded at nearby weather stations. But in northern states or countries, weather stations may not be available due to a sparse population. Thus, there is another type of weather data used—freezing degree-days (FDDs)—which is more easily accessible. In this study, we correlated FDDs to geographic location and icing conditions. A degree-day (DD) is a means of describing the magnitude and duration of time that the mean daily air temperature differs from any specified temperature. Freezing-degree-days (FDDs) are calculated for each day of a season:

$$FDD = (32 - Ta) \tag{1}$$

where Ta is the average daily air temperature in degrees Fahrenheit. A negative freezing degree-day value represents temperatures warmer than freezing, while a positive freezing degree-day represents temperatures below freezing. The FDD values for each day of the winter are summed to determine the net accumulated freezing degree-days (AFDDs).

In terms of ice formation, it is measured in FDDs that grow ice. Every degree of temperature that the mean daily temperature departs from a given base value is one degree-day. For example, if we specify a base value of 0°C and the mean air temperature for a day is -10°C, then 10 Celsius FDDs have accumulated over the course of that day. Annual freezing indices are defined as the cumulative number of degree-days when air temperatures are below 0°C. A good source of FDDs and annual freezing indices data are available in [21]. In this database, the annual freezing indices are provided for each year from 1901 to 2002 on the 25 km resolution Equal-Area Scalable Earth Grid (EASE-Grid) [21].

5.2 Environmental and Performance Analysis

Increasing application of deicing and/or anti-icing chemicals for winter road maintenance has resulted in greater concentrations of deicer constituents in the environment. Residuals from deicing operations have a deteriorating effect on soil and water quality. The degree of impact may be localized or widespread, and depends on various climatic factors, the type of salts used, and the storage conditions of the salts. A good review article on this subject is available in [22], and a brief summary of the environmental impact is given in Table 3.

Table 3. Environmental impact of deicing chemicals.

Area	**Environmental Impacts**			
	Chlorides	**Organic Chemicals (e.g., CMA, etc.)**	**Abrasives**	**Thermal Method**
Air	Practically don't affect	Realized CO_2 emit a specific smell	Relevant source of dust	Increase the temperature of air
Soil	Tend to accumulate and change natural chemical balance	Short-term effect due to decomposition	From deposits	Don't affect
Water	Increase concentrations of corresponding ions	Absorb oxygen, contribute eutrophication of water courses	Practically don't affect	Don't affect
Roadside vegetation	Repress growth at high concentration	Practically don't affect	Practically don't affect	Don't affect
Overall impression	Impact on roadside vegetation	May contribute problems to water courses, worsen air quality if large amount is used	Worsen air quality	Don't affect
Comments	Need to be restricted near sensitive vegetation	Recommended with cautions	Effective in local roads, intersections.	Effective in most locations; cost is main factor.

5.3 Economical Analysis

In order to make an economic analysis of the de-icing process, two parameters have been considered: NPC (net participants' cost) and COO (cost of operation). NPC is the present value of installation and operation costs of the process over its lifetime [23], calculated according to the total annualized cost [\$/yr] and capital recovery factor [23]:

$$\text{NPC} = \text{Equipment Cost} + \text{Installation Cost} + \text{Lifecycle Operation \& Maintenance (O\&M) Costs} - \text{Utility Incentive Payments} \quad (2)$$

COO is the average cost of materials and labor due to a snow or icing event. The equation for COO is as follows:

$$\text{COO} = \text{Materials Cost} + \text{Manpower Cost} \quad (3)$$

6. Case Study – Knik Arm Bridge

In this section, we apply the methodology developed in Section 5 to determine the most appropriate snow and ice control practice for a proposed bridge—the Knik Arm Crossing Project. We describe the significant factors that should be addressed in a deicing control program. The program focuses on the materials and methods that best address the site conditions.

6.1 Geographic and Meteorological Factors of the Knik Arm Bridge

Knik is on the west bank of the Knik Arm of Cook Inlet (149°43′W longitude, 61°27′N latitude), 17.5 miles northeast of Anchorage in the Matanuska–Susitna Borough [24], as shown in Fig. 2.

Due to Knik's geographic location at high latitude, a major wintertime safety issue of the proposed Knik Arm Bridge is that of freezing moisture on the bridge decks, catching motorists off guard as they approach from adjoining roads. Freezing of pavement moisture occurs on bridges due to an accelerated rate of heat loss that promotes freezing by passing cold air. Black ice forms on a bridge deck when moisture condenses on the pavement and freezes, forming a thin, shiny, slick surface.

The Knik Arm Crossing Project is a plan to construct a cost-affordable, vehicular toll bridge that is about two miles long and crosses Knik Arm, joining the Port of Anchorage and Port MacKenzie areas [25]. The Knik Arm Bridge will provide improved transportation infrastructure, vehicular access, and transportation redundancy [25].

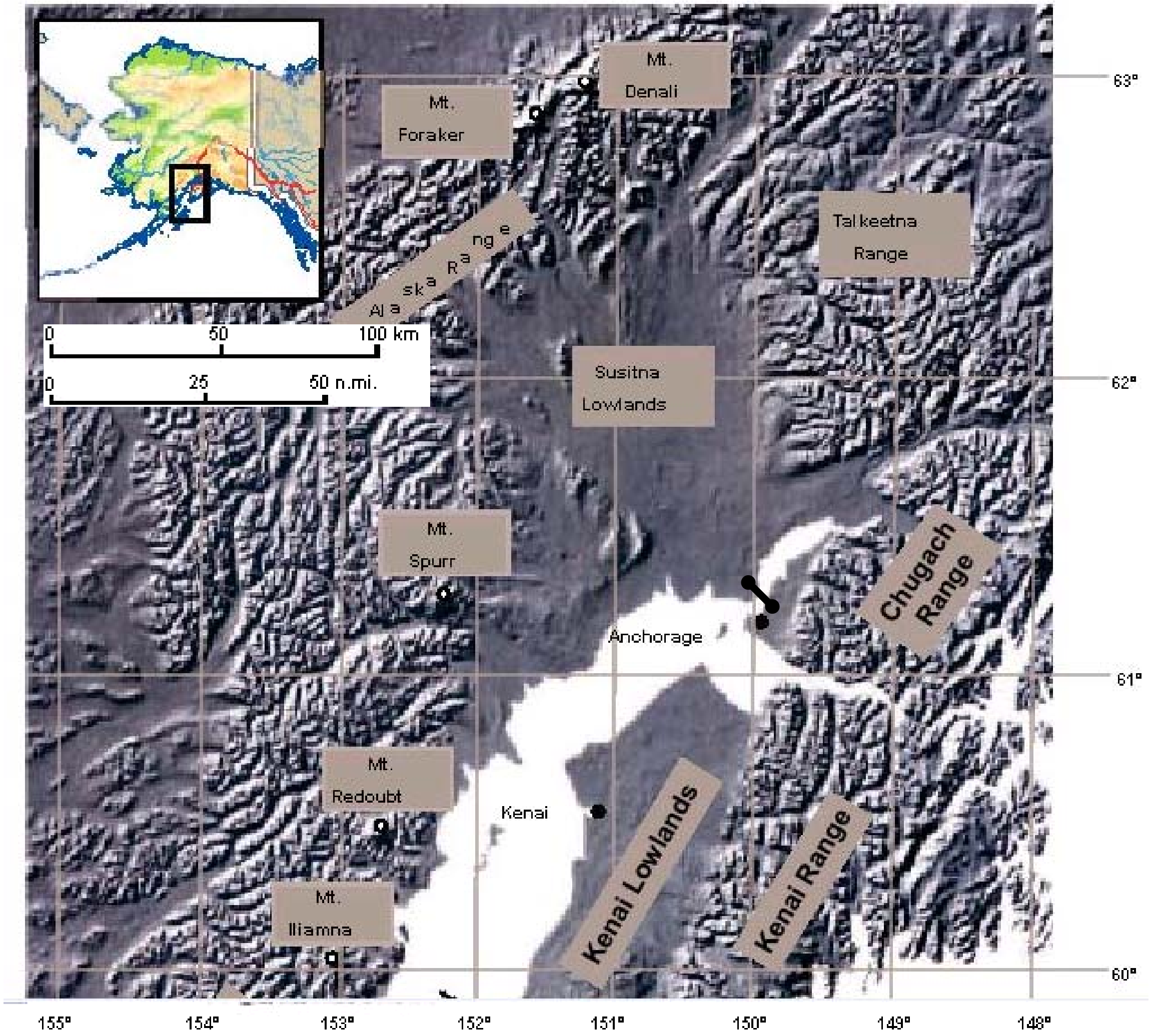

Fig. 2. Cook Inlet and relief map of surrounding region [26]. The proposed Knik Arm Bridge (approximately 150°W longitude, 61.3°N latitude) is represented by a black line.

In order to determine the best deicing program, we collected geographic information as well as meteorological data related to the bridge site. The source of our meteorological data is available from the NOAA (National Oceanic and Atmospheric Administration) National Climate Data Center [27], which maintains an archive of weather conditions reported by the National Weather Service. In this work, a potential icing event is defined as a period of time when the National Weather Service reports some degree of precipitation, with an ambient temperature of

32°F or colder. Our estimates were based on the hourly weather conditions at the Anchorage International Airport for the past nine winter seasons from September 1, 1997, to April 1, 2006. Reported weather conditions flagged as potential icing events range from intermittent rain or snow to continuous or heavy snow. Figure 3 shows a histogram of the events for all nine years. The average yearly number of events is 418, or a cumulative 17.5 days of potentially freezing precipitation. This is likely a lower estimate of the number of potential icing events.

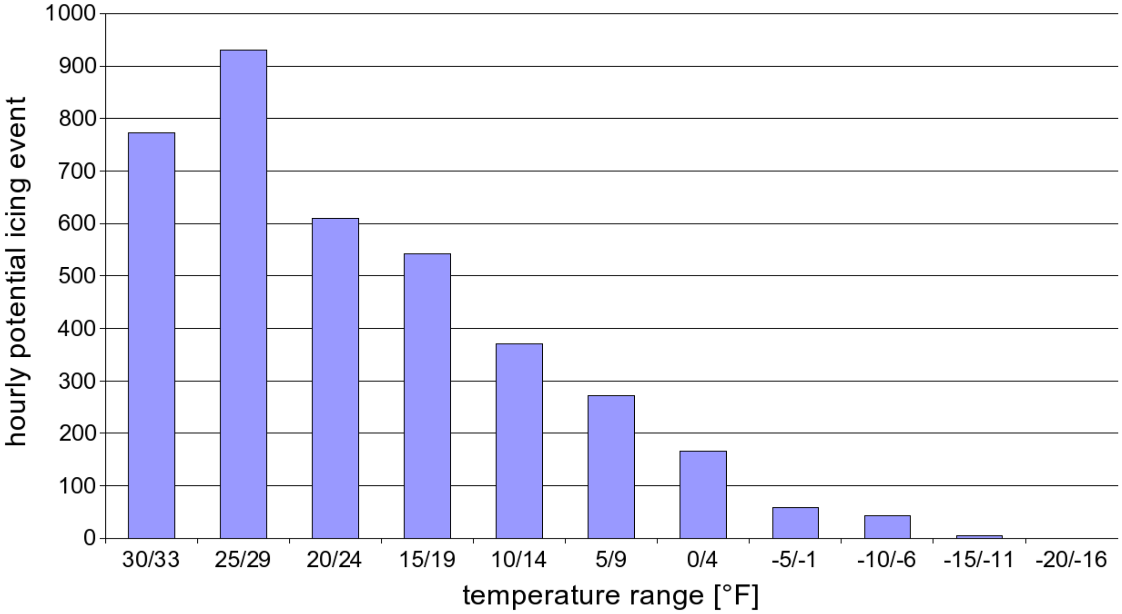

Fig. 3. Potential icing event as a function of temperature at the Anchorage International Airport.

Additional data of meteorological and oceanographic variables have been used to determine the onset of ice in Cook Inlet for the 1970s decade [28]. The analyzed data or factors include FDDs, winds, precipitation amount, river discharge data, and coastal current inflow based on sea surface and air temperatures. Figure 4 shows the mean monthly FDDs for 1974–1997, assuming base temperatures of 0 and -1.8°C for 4 locations on Cook Inlet. We used data from Anchorage because it is one of the ends of the Knik Arm Bridge. NOAA data show that the highest number of consecutive FDD days is 196, when snow on the ground was 0.5 in. or more (period of record is October 23, 1971, to May 5, 1972) [29]. The monthly average temperature in Anchorage is given in Fig. 4 [30]. In the period of interest, that is, from November to March, the average temperature is approximately -10°F.

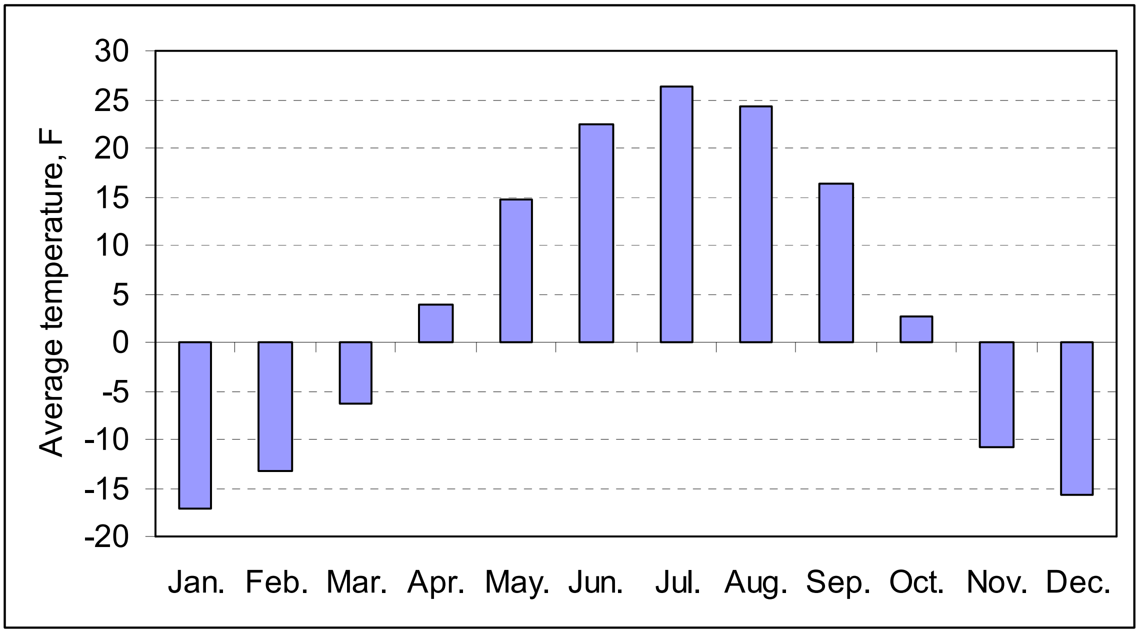

Fig. 4. Average annual temperature (°F) in Anchorage [30].

For the first order of assumption, we use a percentage (e.g., 1%) of the monthly FDDs as the thickness (in inches) of ice in the region of interest. For the Knik Arm Bridge, we used data of the monthly FDDs in Anchorage. Therefore, from Fig. 5, we can estimate that the thickness of ice formation is 10.1 in. from October to April each year.

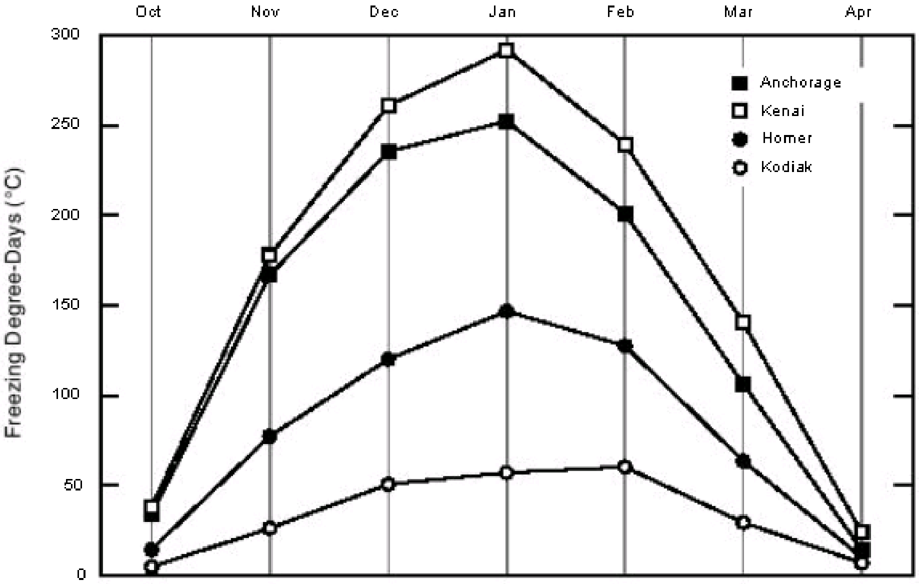

Fig. 5. Mean monthly freezing degree-days (FDDs) for 1974–1997 for four locations on Cook Inlet, assuming base temperatures of 0 and -1.8°C [26].

6.2 Environmental and Performance Analysis of Deicing on the Knik Arm Bridge

With geographic and meteorological information, we determined the optimal deicing materials for the Knik Arm Bridge. Two candidate materials—calcium chloride and potassium acetate—were selected from Table 1, based on their applied temperature range. In practice, calcium chloride is commonly mixed with salt (NaCl). Adding abrasives or thermal methods may also be chosen to complement chemical methods.

In terms of environmental impact, calcium chloride and potassium acetate typically have more negative effects than abrasives and thermal methods. Given that operations would be carried out on a bridge crossing a river close to a sea, most chemical residues probably would drain into the sea and become diluted. For this specific application, the environmental impact of chemicals is minimal.

6.3 Economical Analysis of Deicing on the Knik Arm Bridge

We estimated the cost of chemical and thermal methods using the equations of economical analysis discussed in Section 5.3. For the chemical method, the two species considered were calcium chloride and potassium acetate, as discussed in Section 6.2. We also used the following data in the calculations: ice thickness of 10.1 in. (discussed in Section 6.1) and amount of chemicals (listed in Table 1). For thermal methods, we used the information listed in Table 2. We had limited information for the proposed bridge, presently in its design stage. Some economic data in the case study are from private communication with the Alaska Department of Transportation and Public Services. We made reasonable assumptions about other costs not available in the literature [25]. The final cost of the selected methods is listed in Table 4.

Table 4. Estimated annual cost of typical deicing operations on the Knik Arm Bridge (Unit: $K).

Cost		**Chemical Method**		**Thermal Method** (e.g., thermal fluid)
		Calcium chloride	Potassium acetate	
NPC*	Equipment	20	20	300
	Installation	5	5	400
	Lifecycle (O&M)	2	2	30
	Utility Incentive Payments	0	0	0
COO**	Materials	60	120	100
	Labor	60	60	2
Total cost = NPC + COO		147	207	832

*NPC, net participants' cost; **COO, cost of operation

Table 4 shows that calcium chloride mixed with salt is the most economical chemical method. The thermal method is the most expensive, due to its high NPC (net participants' cost). However, its COO (cost of operation) is lower than chemical methods, and it may be a good candidate when funding of NPC is available.

6.4 Analysis of Ranking

Combining the information in Table 4 and discussion in Sections 6.1 and 6.2, we have ranked various methods based on their effectiveness, cost, and environmental impact: calcium chloride > potassium acetate > thermal method (hot fluid). Clearly, an additional Fixed Automated Spray Technology (FAST) would reduce the amount of chemicals used and the thermal energy applied. As discussed in Section 6.2, the environmental impact of chemicals is minimal due to the proximity of the proposed bridge to the sea.

The ranking is based on theoretical analyses. In the future, an establishment of field test sections would be helpful to verify the effectiveness of selected treatments for snow and ice control.

7. Conclusion

We have developed a methodology of snow and ice control on bridge decks in cold regions. In addition to the applicability of chemical or thermal methods, we considered the geographic, economical, and environmental factors that affect the selection of a specific method.

We demonstrated an application of the methodology to the proposed Knik Arm Bridge. Based on the literature and data from areas of similar latitude, seasonal duration, and intensity of freezing, a chemical method using calcium chloride ($CaCl_2$) mixed with salt (NaCl) is recommended by considering the economic and environmental factors. For special locations, for example, the entrance to a bridge, a thermal method with hot fluid may be considered due to its minimal environmental impact.

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