# Trade-Off Analysis of Nonenvironmental Effects of Alternative Deicers: An Illinois Case Study

CHRIS D. GINGRICH, SARAHELEN R. THOMPSON, ROBERT J. HAUSER, AND J. WAYLAND EHEART

The material, storage, and application costs of salting are low. However, these direct costs understate total costs since salt also damages vehicles, highway structures, and possibly the environment. A framework for estimating the total nonenvironmental costs of deicers is presented, including costs of materials, vehicular damage, and highway structural damage. In addition to salt, the deicers considered are calcium magnesium acetate (CMA), calcium chloride, potassium chloride, urea, methanol, salt with added carboxymethylcellulose, salt mixed with potassium chloride, and salt mixed with urea. Ranking the deicers on the basis of lowest total (nonenvironmental) cost indicates that methanol may be the most attractive deicer for use in Illinois, although more study is needed of methanol's application costs, effectiveness, and dangers. After methanol, salt and salt mixtures are least expensive. CMA is more costly than all other deicers but urea. The cost of CMA and methanol is much higher than the other deicers if vehicle protection costs are not included in the evaluation criteria. In addition, the two deicers that do not harm highway structures, CMA and methanol, are found to be not cost-effective for spot application on concrete bridge decks relative to salt. This is because a significant distance extending beyond the bridge must be treated with CMA or methanol to prevent salt from splashing onto a bridge. Thus, the additional material costs of methanol or CMA are greater than the resulting savings in bridge repair costs.

An issue that is receiving much attention from highway administrators and researchers is the practice of deicing winter roads. The direct costs of salting—involving materials, storage, and application—are low. However, the direct costs understate total costs because salt also damages vehicles, highway structures, and possibly the environment. Murray and Ernst estimate that the total cost may be up to 15 times as great as the direct material costs, excluding environmental damage (*1*). Highway administrators are thus investigating other approaches to maintain winter roads that are potentially less expensive (in an overall societal sense). One such approach is the use of alternative deicers, such as calcium magnesium acetate (CMA), that presumably cause less damage to vehicles, highway structures, and the environment.

This paper presents a framework for estimating the nonenvironmental costs of deicer use, including material, vehicular, and highway structural costs. The cost estimates provide a method of ranking deicers. The framework is used to assess the economics of spot-applying alternative deicers to Illinois bridges. In addition to salt (NaCl), the deicers considered are CMA, calcium chloride ($CaCl_2$), potassium chloride (KCl), urea, methanol, salt with added carboxymethylcellulose (salt/CC), salt mixed with potassium chloride (salt/KCl), and salt mixed with urea (salt/urea). Environmental effects of alternative deicers are discussed by Eheart et al. in another paper in this Record and by Thompson et al. (*2*).

## APPROACH OF STUDY

A restriction imposed throughout the analysis is that the level of deicing effectiveness is maintained at the level currently achieved with salt in Illinois. The restriction is imposed for two reasons: first, in Illinois, and in many other snow-belt states, primary roads are maintained under a bare-pavement policy whenever possible. In Illinois, the bare-pavement policy is enforced on all state roads. Thus, the requirement of deicing effectiveness ensures that the framework reflects actual road maintenance policies. Second, it is necessary to restrict one of the variables (deicing effectiveness, material costs, vehicle damage, or highway structural damage) to compare the costs of "unrestricted" variables. By holding deicing effectiveness constant, it is not necessary to estimate the traffic and safety costs of deicers at different levels of deicing effectiveness—a task beyond the scope of this study.

## MATERIAL COST ESTIMATES

Material cost estimates of deicer use are based on salting practices in Illinois. To predict salting rates throughout the state, a regression model was developed. County data for total annual salt use on state roads for two winter seasons (1988–1989 and 1989–1990) were used to estimate the model. Although there are 102 counties in Illinois, data from only 85 and 96 counties are used in the model's estimations for 1988–1989 and 1989–1990, respectively. Salt data for the remaining counties were either missing or combined with another county.

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C. D. Gingrich, Department of Agricultural Economics, 260 Heady Hall, Iowa State University, Ames, Iowa 50011. S. R. Thompson and R. J. Hauser, Department of Agricultural Economics, 423 Mumford Hall MC-710, University of Illinois, Urbana, Ill. 61801. J. W. Eheart, Department of Civil Engineering, 3217 Newmark Laboratory, 205 North Mathews Street MC-250, University of Illinois, Urbana, Ill. 61801.

After investigating several alternatives, the following specification was chosen:

$$\text{SALT}_{it} = a_1 + a_2\text{SNOW}_{it} + a_3\text{AVEMAX}_{it} + a_4\text{AVEMIN}_{it} + a_{5-12}\text{DIST}_{1-8} + e_{it} \quad (1)$$

where

$\text{SALT}_{it}$ = salt applied on state roads in county $i$ per season $t$ (ton/lane-mi);
$\text{SNOW}_{it}$ = total seasonal snowfall (in.);
$\text{AVEMAX}_{it}$ = seasonal average of mean monthly high temperatures (°F); included are only those months in which total snowfall is greater than or equal to 1 in.;
$\text{AVEMIN}_{it}$ = seasonal average of mean monthly low temperatures (°F); included are only those months in which total snowfall is greater than or equal to 1 in.; and
DIST = binary variables indicating county's Illinois Department of Transportation (IDOT) district; values of district variables are set equal to 1 when in that district, otherwise 0. There are 9 districts in Illinois, with District 9 set as base district.

Estimation results are presented in Table 1 ($N = 181$). The $R^2$ (.816) indicates that the model has a high level of explanatory power. The signs of all the variables conform with expectations, including the temperature variables (mean values for AVEMAX and AVEMIN are 5.6 and −5.3°C, respectively).

The district binary variables are believed to capture the effect of both management practices and traffic. This was borne out by preliminary regression estimates that show traffic to be an insignificant variable when estimated along with the district variables. The traffic variable is the average daily vehicle miles for each county divided by the total number of lane miles in the county. The result is a standardized traffic variable that reduces the variation in traffic arising from multiple-lane highways. Each county's standardized traffic variable is then multiplied by the proportion of state lane miles that make up the county's total lane mileage. This yields a standardized approximation of traffic on state roads. When traffic was included without the district variables, the estimated coefficient on traffic was significant and positive, suggesting that in Illinois heavy traffic causes increased salt applications. However, this particular specification of the model had a substantially lower $R^2$ than the final specification in Equation 1.

To predict an average annual salting rate for a given region, average weather data may be inserted into the model. Complete historical data for each weather variable are not available for all counties in Illinois, but at least one county in each district contains a complete set of weather data. Twenty-year averages for AVEMAX, AVEMIN, and SNOW are computed from these counties and inserted into the model to obtain districtwide application rates. These rates range from 1.50 Mg/km (2.66 tons of salt per lane mile) in southern Illinois to 9.81 Mg/km (17.41 tons per lane mile) in the district containing Chicago. The weighted average annual rate for Illinois is 4.85 Mg/km (8.61 tons per lane mile).

Application rates for the alternative deicers are estimated from the annual salting rates by using substitution rates relative to salt found in the literature (Table 2). Unit prices of each deicer are also presented in Table 2.

Estimates of the storage and application costs of each deicer are based on several approaches suggested in the literature. For salt, Murray and Ernst (*1*) and Bacchus (*3*) assume that storage and application costs are equal to half the cost of purchased materials. For the alternative deicers, Dunn and Schenk (*4*) estimate storage and application costs by adjusting the multiplication factor used for salt (0.5) by each deicer's relative density—the factor most likely to affect storage and application costs. Following the approach of Murray and Ernst and Bacchus, the storage and application costs of salt are assumed to equal half the cost of purchased materials. However, for the alternative deicers, instead of following the exact approach of Dunn and Schenk, this study estimates storage and application costs by adjusting the storage and application cost for salt by the relative density of each deicer (Table 2).

The predicted salting rates and the substitution ratios, purchase prices, and storage and applications costs (Table 2) yield the estimated annual material cost per lane kilometer for each deicer in Illinois. Multiplying the costs per lane kilometer by the number of state lane kilometers yields the estimated an-

**TABLE 1 Estimation of Illinois Salt Application Model**

| Independent Variable | Estimated Coefficient | Standard Error | t Statistic |
|---|---|---|---|
| SNOW | 0.054565 | 0.024571 | 2.22 |
| AVEMAX | -0.23751 | 0.066805 | -3.56 |
| AVEMIN | 0.20216 | 0.069703 | 2.90 |
| DIST1 | 12.831 | 0.95953 | 13.37 |
| DIST2 | 5.6738 | 0.85711 | 6.62 |
| DIST3 | 4.8533 | 0.75127 | 6.46 |
| DIST4 | 2.3456 | 0.83593 | 2.81 |
| DIST5 | 1.4857 | 0.64465 | 2.30 |
| DIST6 | 1.2297 | 0.69525 | 1.77 |
| DIST7 | 0.26447 | 0.61084 | 0.43 |
| DIST8 | 1.7167 | 0.70251 | 2.44 |
| CONSTANT | 7.1675 | 1.9784 | 3.62 |

TABLE 2 Estimated Substitution Ratio, Unit Price, Density, and Storage and Application Costs of Deicers

| Deicer | Substitution Ratio by Weight (relative to salt) | Price ($/Mg) | Density (kgs./m$^3$) | Storage and Application Costs($/Mg) |
|---|---|---|---|---|
| Salt | 1:1 | $24 | 1,135 | $12.10 |
| CMA | 1.5:1 | $682 | 746 | $18.41 |
| $CaCl_2$ | 0.77:1 | $182 | 892 | $15.40 |
| KCl | 1.41:1 | $116 | 1,297 | $10.59 |
| Urea | 2.19:1 | $176 | 1,329 | $10.30 |
| Salt/CC | 0.97:1 | $58 | 973 | $14.11 |
| Salt/KCl | 1.22:1 | $68 | 1,167 | $11.76 |
| Salt/Urea | 0.91:1 | $33 | 1,216 | $11.30 |
| Methanol | 1.19:1 | $200 | 794 | $17.25[a] |

[a] Storage and application costs do not include the costs of new equipment needed to handle liquid methanol.

SOURCES:

Substitution Ratios—CMA (*19,20*), methanol (*4*), all others (*21*). Substitution rate for CMA is based on field tests, substitution rate for methanol is based on methanol's chemical composition, and substitution rates for remaining deicers are based on ice melting tests conducted at -3.89°C for 30 min.

Prices—Salt (*22*), CMA (Chevron Chemical Co., unpublished data), all others [bulk prices of chemical compounds (*23*)]. Price of mixed deicers is obtained by assuming that deicers are combined in same proportion as described by McElroy et al. (*21*).

Density—Salt and CMA (Chevron Chemical Co., unpublished data), methanol and urea (*24*), all others [information from manufacturers (*21*)].

nual material costs of each deicer on state roads in Illinois. The estimated annual material costs per lane kilometer and on state roads by district are given in Table 3. Table 3 shows that salt has the lowest average annual material costs, estimated to be $176/lane-km. CMA has the highest average annual material costs at $5,099/lane-km.

## VEHICULAR COST OF SALTING

To estimate the vehicular costs of road salting, this study follows an approach developed by Menzies (*5*) and TRB (*6*). Several other studies have also estimated the costs of vehicular salt damage (*1,6,7*), but the Menzies and TRB approaches best capture recent changes by manufacturers to improve the corrosion resistance of vehicles. Following these approaches, the vehicular costs of salting may be divided into two components: protection costs and damage costs. Protection costs are the added costs of inputs that inhibit corrosion. Damage costs are equal to reductions in resale value caused by salt damage. However, since vehicles are no longer as susceptible to corrosion as they were 10 years ago (*8*), vehicle damage from salt occurs only in the form of minor cosmetic corrosion.

To estimate the costs of corrosion protection, TRB obtained estimates from manufacturers for the added cost of improved coatings, paints, panels, and other measures designed to reduce vehicle corrosion (*6*). The estimates range from $250 to $800/vehicle for typical late-model cars or, at midpoint, about $500/vehicle. However, not all of the costs of corrosion protection may be attributed to salt. Other factors such as sea spray, acid rain, and air pollution also cause vehicle corrosion. Hence, even if road salting were eliminated it is unlikely that the amount of corrosion protection added by manufacturers would significantly decrease. In light of these issues, based on discussions with motor vehicle manufacturers, TRB estimated that savings in the cost of corrosion protection would be $125 to $250/vehicle if salt (and calcium chloride) were no longer used for highway deicing. These savings would largely result from the reduced application of galvanized steel. In this study, an estimate of $200/vehicle is assumed to be the amount of protection cost per vehicle attributable to salt.

To estimate the vehicular damage costs of salt, Menzies compares rates of vehicle depreciation in three areas of the United States with different salting practices (*5*). New England is chosen as a region with high salting rates, the Mid-Atlantic as a region with moderate salting rates, and the Southeast as a region that does not use road salt. Menzies acknowledges that the approach is a simplification in that it ignores the effect of regional incomes, pollution, and the fact that vehicles may be traded between regions. Nonetheless, the average annual depreciation rates of automobiles in New England, the Mid-Atlantic, and the Southeast are estimated to be 15.9, 15.6, and 15.4 percent, respectively, which are consistent with the rates expected from the regional salting practices. Applying the depreciation rates to the average price of a new car ($15,403) and the average vehicle age in the United States (7.6 years) yields annual salt damage costs of $25/vehicle in New England and $10/vehicle in the Mid-Atlantic or, on average, about $17/vehicle.

The estimates of the costs of vehicle protection and damage from road salt may be applied to Illinois. The protection cost per vehicle ($200) is multiplied by the number of new cars

**TABLE 3 Estimated Annual Material Costs of Deicers on State Roads in Illinois, by District**

| Deicer: | District: | | | | | | | | | Average Cost per Lane km | Illinois Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | |
| Salt | $357<br>$5,535 | $208<br>$1,671 | $175<br>$1,471 | $129<br>$655 | $113<br>$855 | $91<br>$741 | $63<br>$324 | $98<br>$664 | $55<br>$234 | $176 | $12,150 |
| CMA | $10,309<br>$160,188 | $6,016<br>$48,368 | $5,063<br>$42,582 | $3,731<br>$18,966 | $3,292<br>$24,737 | $2,641<br>$21,449 | $1,806<br>$9,370 | $2,837<br>$19,218 | $1,575<br>$6,776 | $5,099 | $351,653 |
| $CaCl_2$ | $1,488<br>$23,116 | $868<br>$6,980 | $730<br>$6,145 | $538<br>$2,737 | $475<br>$3,570 | $381<br>$3,095 | $260<br>$1,352 | $409<br>$2,773 | $228<br>$978 | $736 | $50,746 |
| KCl | $1,745<br>$27,107 | $1,018<br>$8,185 | $857<br>$7,206 | $631<br>$3,209 | $557<br>$4,186 | $447<br>$3,630 | $306<br>$1,585 | $480<br>$3,252 | $267<br>$1,147 | $863 | $59,506 |
| Urea | $4,003<br>$62,207 | $2,336<br>$18,783 | $1,966<br>$16,536 | $1,449<br>$7,365 | $1,278<br>$9,606 | $1,025<br>$8,330 | $701<br>$3,639 | $1,102<br>$7,463 | $612<br>$2,631 | $1,980 | $136,561 |
| Salt/CC | $687<br>$10,674 | $401<br>$3,223 | $337<br>$2,838 | $249<br>$1,264 | $219<br>$1,648 | $176<br>$1,429 | $120<br>$624 | $189<br>$1,281 | $105<br>$452 | $340 | $23,433 |
| Salt/KCl | $999<br>$15,521 | $583<br>$4,686 | $490<br>$4,126 | $361<br>$1,838 | $319<br>$2,397 | $256<br>$2,078 | $175<br>$908 | $275<br>$1,862 | $153<br>$657 | $494 | $34,072 |
| Salt/Urea | $398<br>$6,188 | $233<br>$1,869 | $195<br>$1,645 | $144<br>$733 | $127<br>$956 | $102<br>$829 | $70<br>$362 | $110<br>$742 | $61<br>$262 | $197 | $13,585 |
| Methanol | $2,536<br>$39,397 | $1,480<br>$11,896 | $1,245<br>$10,473 | $918<br>$4,665 | $810<br>$6,084 | $650<br>$5,275 | $444<br>$2,304 | $698<br>$4,726 | $388<br>$1,667 | $1,254 | $86,487 |

The first number in each cell is the cost per lane km in dollars. The second number is the cost on state roads in thousand dollars.

and trucks bought each year. Data are available for the entire state only. Vehicle sales in each district are estimated by the proportion of registered vehicles in each district. The annual damage cost per vehicle ($17) is multiplied by the number of registered cars and trucks in each district. Adding the annual vehicular protection and damage costs yields more than $266 million: $145 million for protection costs and $121 million for damage costs (Table 4).

## HIGHWAY STRUCTURAL DAMAGE

Two methods are used to estimate the amount of highway structural damage caused by salt in Illinois. First, the method developed in the TRB study (*6*) is used to estimate the annual costs of salt damage to concrete bridge decks. Second, a model of bridge deck deterioration, as suggested by Vitaliano (*7*), is used to determine the impact of salt on bridge deck con-

**TABLE 4 Annual Vehicular Costs of Salt in Illinois, by District**

| District | Protection Costs | Damage Costs | Total |
|---|---|---|---|
| 1 | $74,195 | $59,985 | $134,181 |
| 2 | $14,314 | $12,025 | $26,339 |
| 3 | $9,213 | $7,785 | $16,998 |
| 4 | $8,343 | $7,067 | $15,410 |
| 5 | $9,461 | $8,059 | $17,520 |
| 6 | $9,381 | $8,038 | $17,420 |
| 7 | $4,964 | $4,324 | $9,288 |
| 8 | $11,125 | $9,423 | $20,548 |
| 9 | $4,633 | $4,008 | $8,640 |
| Total | $145,629 | $120,714 | $266,343 |

NOTE: Costs given in thousands of dollars.

dition, predict the life of a bridge deck, and compute the cost of salting to bridge decks in present-value terms. Finally, both approaches are used to assess the economics of spot-applying alternative deicers on bridges.

This section focuses on concrete bridge decks, since they are the highway structural component most vulnerable to salt damage (*9,10*). In particular, concrete bridge decks are vulnerable to spalling, which occurs when chloride ions penetrate reinforced concrete and cause steel reinforcing rebars to corrode and rupture the surrounding concrete. Highways and other bridge components are much less susceptible to salt damage than concrete bridge decks because they are built with less reinforcing steel and receive lesser amounts of salt.

The TRB approach separates salting costs into two components: protection costs and damage costs. Bridges constructed with inputs such as epoxy-coated rebars, concrete overlays, or interlayer membranes are highly resistant to spalling. The cost of these inputs may be attributed to salt. It would not be reasonable to attribute all of the costs of deck protection to salt in coastal areas where sea spray also causes spalling. To estimate the annual costs of protecting bridge decks against salt damage, the number of bridges built per year and their average area are multiplied by the cost per square foot of installing corrosion protection. In Illinois, epoxy-coated rebars are the primary method of bridge deck protection. With the cost of epoxy coating estimated at \$18.17/m$^2$ (\$1.69/ft$^2$), the annual cost of protecting bridges against salt damage in Illinois is estimated (Table 5). The cost of epoxy coating comes from Babaei and Hawkins (*11*), adjusted for inflation at an annual rate of 4 percent.

To estimate the costs of repairing salt damage on bridge decks, the TRB study focuses on bridges that are susceptible to damage from current salt applications. Such bridges are not constructed with corrosion protection, show no visible signs of salt damage, and are not contaminated with chloride ions. In this study a bridge is considered protected if it was built with either epoxy-coated rebars or a concrete protection system including low-slump, polymer-impregnated, or latex-modified concrete (*11*). It is assumed that an unprotected bridge exposed to salt for more than 10 years is already contaminated with chloride ions even if it shows no visible signs of damage. The number of bridges that will become damaged over the next 10 years is predicted by multiplying the proportion of unprotected bridges (10 to 20 years old) with deck damage by the number of bridges susceptible to current salt applications. Bridge deck condition is rated by FHWA on a scale of 0 to 9, with 9 indicating a deck in perfect condition. In this study a deck is considered damaged if it has a rating of 6 or less. Multiplying the number of bridges expected to become damaged by their average area yields the total bridge deck area that will need repair over the next 10 years. Dividing the total area by 10 yields the annual area requiring repair. Applying the approach to Illinois with an estimated repair cost of \$215/m$^2$ (\$20/ft$^2$) yields the estimated annual cost of bridge deck damage from salt (Table 6). The annual costs of applying salt on Illinois bridges are estimated with the TRB approach to be \$4 million to protect new bridges and \$5 million to repair existing salt damage.

The second method of estimating salt damage to concrete bridge decks is based on a model of bridge deck deterioration, as suggested by Vitaliano (*7*). The deck deterioration model was estimated with different specifications using a procedure for ordinally ranked, limited dependent variables as suggested by McKelvey and Zavoina (*12*). Bridges included in the model have a reinforced concrete deck, are maintained by the state, and were built or reconstructed after 1970. The following specification produced the best model in terms of explanatory power and coefficient significance:

$$C = a_1 + a_2\text{AGE} + a_3\text{ADT}^2 + a_4\text{AGESALT} + a_5\text{DPROT} + e \qquad (2)$$

where

$C$ = present bridge deck condition rating represented by index value of integers 0 through 9;

**TABLE 5 Estimated Annual Costs of Protecting Concrete Bridge Decks from Salt in Illinois, by District**

| District | Ave. Area of Bridges Built, 1980-1989 (m$^2$) | Ave Number of Bridges Built per Year, 1980-89 | Annual Protection Cost Against Salt Damage (\$18.17 per m$^2$) |
|---|---|---|---|
| 1 | 1,432 | 35.4 | \$921,946 |
| 2 | 377 | 70.2 | \$481,285 |
| 3 | 341 | 70.8 | \$438,822 |
| 4 | 451 | 40.3 | \$330,543 |
| 5 | 232 | 77.3 | \$326,684 |
| 6 | 373 | 68.0 | \$461,487 |
| 7 | 226 | 53.9 | \$221,866 |
| 8 | 798 | 39.1 | \$567,673 |
| 9 | 199 | 43.5 | \$157,723 |
| Total | 431 | 498.5 | \$3,905,791 |

**TABLE 6 Estimated Annual Bridge Deck Damage from Salt in Illinois, by District**

| District | No. of Unprotected Bridges, Built 1980-89, No Deck Damage | Ave. Area of Susceptible Bridges ($m^2$) | Unprotected 10-20 Year Old Bridges with Damage | Estimated Annual Damage Costs From Salt at \$215 per $m^2$ |
|---|---|---|---|---|
| 1 | 180 | 943 | 39% | \$1,423,937 |
| 2 | 554 | 354 | 27% | \$1,138,304 |
| 3 | 550 | 237 | 8% | \$224,224 |
| 4 | 341 | 456 | 21% | \$701,778 |
| 5 | 715 | 228 | 9% | \$315,701 |
| 6 | 569 | 327 | 16% | \$639,465 |
| 7 | 440 | 202 | 23% | \$439,208 |
| 8 | 285 | 414 | 30% | \$761,634 |
| 9 | 379 | 202 | 11% | \$181,435 |
| Total | 4,013 | 320 | 18% | \$4,969,699 |

AGE = current age of bridge or, if rebuilt, number of years since reconstruction;
$\text{ADT}^2$ = average daily traffic (ADT) on bridge, in number of cars and trucks squared;
AGESALT = AGE variable multiplied by average annual tons of salt per lane mile. Salting rates are assigned according to bridge's respective IDOT district as predicted from salt application model (Table 2);
DPROT = binary variable equal to 1 if bridge was built with epoxy-coated rebars, and equal to 0 otherwise; and
$e$ = error term.

The estimation results are as follows ($t$-statistics for each coefficient are in parentheses):

$$C = \underset{(35.27)}{7.62} - \underset{(-13.91)}{.074\text{AGE}} - \underset{(-6.15)}{1.14 \times 10^{-10}\text{ADT}^2}$$

$$- \underset{(-6.41)}{.0029\text{AGESALT}} + \underset{(14.04)}{1.007\text{DPROT}} \qquad (3)$$

The signs of all the variables are consistent with the expected results and are highly significant. However, much of the variation in bridge deck condition is unexplained by the model ($R^2 = .276$, $N = 1{,}879$). The most likely explanation for this phenomenon is the omission of factors affecting deck condition that could not be quantified.

Equation 2 may be solved for the value of AGE equal to the number of years (LIFE) needed to reach a given deck condition ($C$).

$$\text{LIFE} = (C - a_1 - a_3\text{ADT}^2 - a_5\text{DPROT})/(a_2 + a_4\text{SALT}) \qquad (4)$$

Equation 4 allows the cost of salt damage to bridge decks to be measured in terms of the present-value cost of expected deck repair. Future repair costs are discounted by a bridge's predicted life at a given salting rate and at zero salt conditions. The difference between the two costs provides a measure of the present-value cost of salt damage to bridge decks. Inserting the predicted Illinois salting rates, mean values for $\text{ADT}^2$ and DPROT, and a critical deck condition of 6 into Equation 4 yields present-value estimates of salt damage on bridge decks in Illinois (Table 7). The cost of deck repair is again assumed to be \$215/$m^2$ (\$20/$ft^2$, as in the TRB approach) and the discount rate is chosen at 7 percent per year. The results obtained from the deck deterioration model show that the average salt damage per square meter of bridge deck in Illinois, measured in present-value terms, is estimated to be \$21.40. The estimates range from \$6.99 to \$39.35/$m^2$ (\$0.65 to \$3.66/$ft^2$) across districts due to variations in the salting rate.

## SPOT APPLICATION OF ALTERNATIVE DEICERS ON BRIDGES

A review of the literature suggests that two alternative deicers—CMA and methanol—do not damage bridges (*4,13,14*). Moreover, a comprehensive analysis of CMA damage (*15*,p.90) indicates that "asphalts, plastics, elastomers, ceramics, wood, sign sheetings and paints, rubber compounds, sealers, and adhesives appeared to be either unaffected by solutions of sodium chloride or calcium magnesium acetate, or similarly affected," and that salt causes corrosion problems whereas CMA does not. However, both of these deicers have material costs higher than that of salt. For either CMA or methanol to be cost-effective for spot application on bridges, their additional material costs must be less than the resulting savings in bridge repair costs.

The TRB approach of estimating the annual costs of salt damage on bridges does not address the question of spot-applying alternative deicers on bridges. However, the concepts underlying the TRB approach may be extended to assess spot applications by comparing the annual repair costs of salt damage with the additional material costs of using CMA and methanol on bridges susceptible to salt damage.

**TABLE 7 Estimated Present Value of Salt Damage to Concrete Bridge Decks in Illinois, by District**

| District | Salting Rate (ann. Mgs/lane km) | Life (years) | Present Value of Deck Repairs (per m$^2$) | Present Value of Salt Damage (per m$^2$) |
|---|---|---|---|---|
| 1 | 9.75 | 14.50 | $80.63 | $39.35 |
| 2 | 5.69 | 17.45 | $66.01 | $24.83 |
| 3 | 4.79 | 18.28 | $62.46 | $21.18 |
| 4 | 3.53 | 19.58 | $57.19 | $16.02 |
| 5 | 3.11 | 20.04 | $55.36 | $14.19 |
| 6 | 2.50 | 20.78 | $52.68 | $11.50 |
| 7 | 1.71 | 21.81 | $49.13 | $7.96 |
| 8 | 2.68 | 20.55 | $53.54 | $12.36 |
| 9 | 1.49 | 22.11 | $48.16 | $6.99 |
| Illinois Average | 4.82 | 18.25 | $62.57 | $21.39 |
| Zero Salt | 0.00 | 24.2 | $41.17 | $0.00 |

The additional material costs of CMA and methanol are obtained by subtracting the material costs of using salt on bridges susceptible to salt damage from the material costs of using CMA and methanol on those same bridges. The total bridge area susceptible to salt damage is taken from Table 6. Converting the total area from square meters to lane kilometers and applying the respective material costs per lane kilometer (Table 3) yields the annual material costs of salt, CMA, and methanol. The material costs of salt are then subtracted from the material costs of CMA and methanol. The potential savings in bridge damage from CMA and methanol use are equal to the estimated annual costs of salt damage in Table 6.

Two more costs would arise if CMA or methanol were spot-applied on bridges. First, labor and equipment costs would increase as road maintenance crews assigned spreaders and personnel to apply a single deicer selectively throughout a maintenance area. A rough estimate of these additional costs is found by increasing the application and storage costs of CMA and methanol by some factor. An arbitrary factor of 5 is used in this example. The second additional cost of spot-applying CMA or methanol on bridges stems from the distance extending from each bridge that must be treated with CMA or methanol so that salt applied on the highway does not splash onto the bridge. Evidence from actual spot application sites (Michigan Department of Transportation has spot-applied CMA on the Zilwaukee bridge near Saginaw since 1987) suggests that the minimum distance should be 1.61 km (1 mi). In this study, distances of 0, 15.25, 61, and 750 m (0, 50, 200, and 2,640 ft) are considered.

The financial assessment of CMA and methanol use on bridges using the TRB approach is presented in Table 8. The cost figures are the annual net savings of CMA and methanol use for spot applications on bridges. The assessment indicates that neither CMA nor methanol is cost-effective to apply on bridges if the minimum distance extending the bridge treated with CMA or methanol is 750 m. At a distance of 750 m, the use of CMA and methanol on bridges in Illinois results in annual net increases in expenditures of $80 million and $20 million, respectively. Only if the distance extending from a bridge requiring CMA or methanol is significantly reduced (to 15.25 and 61 m, respectively) does either CMA or methanol become cost-effective to apply on Illinois bridges.

The economics of spot-applying CMA and methanol on bridges may also be assessed with Vitaliano's deck deterioration model (*7*). Similar to the assessment using the TRB approach, the costs of salt damage are compared with the additional material costs of CMA and methanol. However, use of the deck deterioration model allows for the costs of salt damage and the additional material costs of CMA and methanol to be discounted over the expected life of a bridge to a present-value basis.

The net savings from CMA and methanol use are estimated in the following manner. The added material costs of CMA and methanol are converted to a present-value basis by discounting over the predicted bridge life under zero salt conditions a constant stream of additional annual material costs. An annual rate of 7 percent is used to discount the added material costs of CMA or methanol; this is the same rate used to discount future repair costs. The additional material costs, converted from kilometers to square meters, are then subtracted from the present value of the salt damage costs (Table 7) to obtain the present-value net savings from CMA and methanol use per square meter of bridge deck. The two additional costs of spot-applying CMA and methanol discussed for the TRB approach are also considered. The storage and application costs of CMA and methanol are multiplied by 5 to allow for added equipment and labor costs, and distances of 0, 15.25, 61, and 750 m are considered for the distance extending each bridge treated with CMA or methanol.

The assessment of spot-applying CMA and methanol on bridges using the deck deterioration model is presented in Table 9. The assessment shows that both CMA and methanol use on Illinois bridges results in increased expenditures if the distance extending the bridge treated with CMA or methanol is 750 m ($619 and $166/m$^2$, respectively, in present-value

**TABLE 8 Estimated Annual Net Savings of Spot-Applying CMA and Methanol on Bridges in Illinois, by District**

| | Distance treated with CMA or methanol extending from each bridge (m) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 | | 15.25 | | 61 | | 750 | |
| District | CMA | Meth | CMA | Meth | CMA | Meth | CMA | Meth |
| 1 | $911 | $1,285 | $685 | $1,219 | $9 | $1,021 | ($10,997) | ($2,207) |
| 2 | $801 | $1,053 | $525 | $972 | ($302) | $729 | ($13,755) | ($3,216) |
| 3 | $37 | $178 | ($178) | $115 | ($824) | ($74) | ($11,338) | ($3,157) |
| 4 | $542 | $666 | $441 | $636 | $138 | $547 | ($4,787) | ($897) |
| 5 | $169 | $284 | ($11) | $231 | ($551) | $73 | ($9,342) | ($2,505) |
| 6 | $509 | $614 | $392 | $580 | $42 | $477 | ($5,652) | ($1,193) |
| 7 | $399 | $434 | $342 | $417 | $170 | $367 | ($2,623) | ($453) |
| 8 | $672 | $743 | $607 | $724 | $413 | $667 | ($2,750) | ($260) |
| 9 | $152 | $178 | $109 | $165 | ($23) | $127 | ($2,162) | ($501) |
| Illinois | $3,115 | $4,514 | $1,491 | $4,038 | ($3,378) | $2,610 | ($82,593) | ($20,620) |

NOTE: Savings given in thousands of dollars.

**TABLE 9 Net Savings of Spot-Applying CMA and Methanol on Bridges in Illinois per Square Meter of Bridge Deck, by District, Using Deck Deterioration Model**

| | Distance treated with CMA or methanol extending from each bridge (m) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 | | 15.25 | | 61 | | 750 | |
| District | CMA | Meth | CMA | Meth | CMA | Meth | CMA | Meth |
| 1 | $4.52 | $30.00 | ($7.42) | $26.45 | ($43.12) | $16.02 | ($623.98) | ($154.41) |
| 2 | $4.41 | $19.25 | ($11.61) | $14.62 | ($59.89) | $.43 | ($844.09) | ($229.57) |
| 3 | $4.09 | $16.56 | ($10.11) | $12.47 | ($52.69) | ($.11) | ($745.05) | ($203.12) |
| 4 | $3.33 | $12.58 | ($4.84) | $10.22 | ($29.25) | $3.01 | ($426.56) | ($113.55) |
| 5 | $3.01 | $11.18 | ($9.68) | $7.42 | ($47.96) | ($3.76) | ($670.11) | ($186.24) |
| 6 | $2.58 | $9.14 | ($3.98) | $7.20 | ($23.76) | $1.40 | ($344.62) | ($92.69) |
| 7 | $1.83 | $6.34 | ($5.05) | $4.30 | ($25.91) | ($1.83) | ($364.95) | ($101.29) |
| 8 | $2.69 | $9.68 | ($1.29) | $8.60 | ($13.23) | $5.05 | ($207.53) | ($51.94) |
| 9 | $1.61 | $5.48 | ($5.16) | $3.55 | ($25.59) | ($2.47) | ($358.39) | ($100.11) |
| Average | $4.09 | $16.67 | ($7.74) | $13.23 | ($43.12) | $2.80 | ($619.03) | ($166.02) |

Figures in parentheses represent additional net costs.

terms). If the distance is decreased to 61 m, methanol becomes cost-effective. However, CMA becomes cost-effective only if the distance can be decreased to zero.

## TOTAL COST OF DEICERS

Total cost estimates are obtained by adding the material, vehicular, and highway structural costs of each deicer. CMA and methanol are assumed not to harm vehicles and bridges (*4,13–15*); hence their total costs are equal to the costs of materials (purchase, storage, and application) only. The vehicle and bridge damage costs of the remaining deicers are assumed to be identical to those of salt. A review of the literature suggests that $CaCl_2$ and urea also damage vehicles and bridges, although not to the same extent as salt (*4,13,16,17*). There is no explicit mention of the effects of KCl in the literature review, but KCl is a metallic salt containing the chloride ion and thus is assumed to behave similarly to salt and $CaCl_2$. However, the amount of salt damage to vehicles and bridges varies little with changes in the salting rate once the concentration of salt reaches a certain level (*4*). Consequently, a slight reduction in salt use—as with a combination deicer containing salt—or the use of a slightly less damaging deicer would presumably not cause a significant decrease in the total amount of vehicle and bridge damage.

The material cost estimates for each deicer are based on applications on Illinois state roads only because salting rates on nonstate roads are unknown. Thus, material costs are somewhat understated. However, it should be emphasized that in order to assume zero vehicle or bridge damage costs for CMA and methanol, they must be applied on all roads and highways traveled by Illinois vehicles.

The sum of each deicer's material, vehicular, and highway structural costs is presented in Figure 1. The results suggest that for Illinois methanol is the lowest-cost deicer. The total annual cost of using methanol in place of salt is estimated to be $90 million, although this does not include the unique application and storage costs associated with liquid methanol. However, even if the annual costs of methanol were to double as a result of higher application and storage costs, methanol would remain the lowest-cost alternative deicer. The total annual cost of current salting practices in Illinois (excluding environmental damage) is estimated at almost $290 million. Combination deicers involving salt (salt/CC, salt/KCl, and salt/urea) are only slightly more expensive than salt alone, ranging between $290 million and $310 million in total annual costs. Among the remaining deicers, urea has the highest annual total cost, estimated to be more than $410 million. CMA is the next most expensive deicer, with a total annual cost of $351 million, which is entirely a function of its high material cost.

Further research into the use of methanol for deicing purposes should be undertaken before methanol can be considered a complete replacement for salt. Although preliminary laboratory and field testing of methanol indicates that it is an effective deicer (*4*), methanol evaporates very quickly and thus may be impractical for widespread use. Methanol is also a commonly used cleaning solvent. Therefore, its use may damage paint on vehicles. Tests by the Illinois Department of Transportation (*18*) indicate that heavy concentrations of methanol damage lacquer automobile paint but not enamel paint. Paint damage is ignored in this study but should be considered in future evaluations of methanol as a road deicer.

## CONCLUSION

This paper presents a framework for estimating the total costs of deicers, including the costs of materials and damage to vehicles and highway structures. The framework is applied to Illinois. Ranking the alternative deicers on the basis of lowest total (nonenvironmental) cost indicates that methanol may be the most attractive deicer for use in Illinois, although more study is needed of methanol's application costs, effectiveness, and dangers. After methanol, salt and salt mixtures are the least costly deicers. CMA is more expensive than all deicers except urea. The cost of CMA and methanol is much higher than the other deicers if vehicle protection costs are not included in the evaluation criteria.

In addition, it was determined that the two deicers that do not harm highway structures—CMA and methanol—are not cost-effective for spot application on concrete bridge decks relative to salt. This is because a significant distance extending beyond the bridge must be treated with CMA or methanol to prevent salt from splashing onto a bridge. Thus, the additional material costs of methanol or CMA are greater than the resulting savings in bridge repair costs.

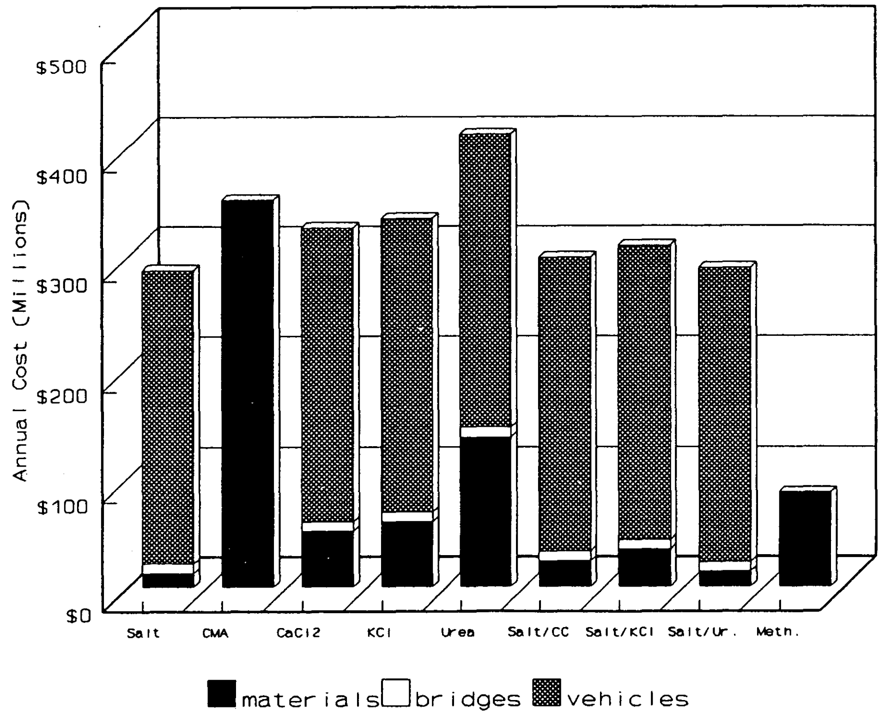

**FIGURE 1 Estimated total annual cost of deicers in Illinois.**

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