Benefit-Cost Assessment of the Utility of Road Weather Information Systems for Snow and Ice Control

S. EDWARD BOSELLY III

In 1988, the Strategic Highway Research Program initiated a project to look at the potential effectiveness of road weather information system technologies for improving and reducing costs of highway snow and ice control. These technologies include pavement and meteorological sensors, pavement and weather condition forecasts, roadway thermography, and the communications, both human and electronic, required for effective dissemination of the information. The investigation required the performance of a benefit-cost analysis of road technologies. The benefit-cost assessment is complex because it has to take into account variations in the distribution of weather events and road conditions, as well as snow and ice control practices, in different regions of the country. Described in this paper is the statistical model used to perform the benefit-cost assessment, to include the one-, two-, and three-dimensional matrices that form the basis for computing costs. Benefits are the reductions in snow and ice control costs resulting from the use of the weather information technologies. Finally, presented in the paper are the results obtained from running the model. Model results show that the use of weather technologies can be cost-effective when decisions become proactive with the use of weather information. The model shows that detailed forecasts of road conditions provide the greatest benefit-cost ratio; however, the combination of forecasts, sensors, and road thermography synergistically provides improved level of service for snow and ice control, and a significant reduction in decision errors, as well as a benefit-cost ratio greater than one.

Research under the Strategic Highway Research Program (SHRP) Contract H-207, Storm Monitoring/Communications, has shown that weather information can improve highway maintenance managers' ability to assign their labor, equipment, and materials for snow and ice control. By becoming proactive with information, rather than reactive to conditions, more timely and efficient decisions can be made. Described in this paper are a methodology and computer model developed to quantify the benefits of using road weather information system (RWIS) data compared with the costs of reacting to present conditions.

Because of weather patterns, many European countries experience a high frequency of icing conditions on their roadways. This, combined with relatively high population and traffic densities, drives a need to provide improved snow and ice control response. Today, in some European countries, RWIS are implemented countrywide. Forecasts of road temperatures and conditions, as well as weather conditions, are commonplace. Meteorological and pavement sensors monitor conditions in the road environment. Road thermography, a technology which was developed in the United Kingdom, employs instrumented vehicles and downward-pointing infrared radiometers to create temperature profiles of road surfaces. Climate and weather consultants work closely with highway maintenance agencies to form a common understanding of abilities and needs related to road weather information.

In order to foster an exchange of information, a European forum evolved, devoted to the subject of road weather: the Standing European Road Weather Commission (SERWEC), which meets every 2 years, and every 4 years in conjunction with the Permanent International Association of Road Congresses (PIARC). In 1990, SERWEC became SIRWEC, the I standing for International, with the addition of members from the United States and Asia. In addition, the European Community sponsors research on the road weather information systems through the Cooperation in Science and Technology project. However, much of this European development is a result of governmental support. In Europe, a completely packaged RWIS can frequently be found that is backed by government-subsidized consultants and hardware manufacturers, all of whom work closely with their national meterological service.

In the United States, however, the implementation of RWIS technology has not taken hold as rapidly. Each state highway agency has its own budgets and policies, but not all have research programs; and each state highway agency tends to rely on its own resources to identify or implement innovations. Autonomy also exists between state and federal agencies that need weather information. In fact, it is a credit to the industriousness and marketing talents of one United States vendor of RWIS technology that RWIS hardware is in place in some of this nation's roadways. These systems, originally designed for airports, where snow and ice control are also significant winter problems, are now being put to roadway use.

In 1988, SHRP initiated a project to investigate the use of TWIS technologies to provide guidance to the states on how to implement the technologies should they be proven effective. The investigation involved defining the state of the art in RWIS sensors; identifying the communications required for disseminating the information, assessing the ability of the meterological community to provide support for decision makers, and determining whether the technologies are cost-effective. SHRP contracted with The Matrix Management Group, who, with its subcontractors, the Washington State Transportation Center (TRAC) at the University of Wash-

The Matrix Management Group, 811 1st Ave., Suite 466, Seattle, Washington 98104.

ington, and the University of Birmingham in the United Kingdom, have conducted the investigation.

Questionnaire surveys were sent to all states and provinces of Canada; in-person interviews were conducted in 10 states and one province of Canada. The information was required in order to determine whether the RWIS technology is feasible and cost-effective. Early indications from some state highway agency tests indicated that savings of up to 10 percent of snow and ice control costs might be possible through the use of RWIS technologies. The survey results and Federal Highway Administration statistics show that the cost of snow and ice control in the United States and Canada exceeds $2 billion per year (*1*). Even a 1 percent reduction in this figure would generate at least a $20 million saving.

Field testing for the SHRP investigation involved seven states: Colorado, Massachusetts, Michigan, Minnesota, Missouri, New Jersey, and Washington. These states were selected because they are located in different climate areas, they have different snow and ice control practices, and each had elected to test some forms of RWIS technology. Additional assistance and data were obtained from the following three states.

- The Minnesota Department of Transportation (DOT) had installed one brand of sensors in the Minneapolis area; installed a second brand at its road research facility near Monticello, which could be used in analyzing variations in pavement temperatures across lanes of traffic; installed a third brand in the Duluth area; had also contracted for road thermographic and climatologic analysis in Duluth; had contracted for weather forecasting services to support snow and ice control managers; and had hired a meteorologist as a staff weather advisor.
- The Colorado Department of Highways had installed a large number of sensors in the Denver area that could be used for analysis of the spatial variability of temperatures and requirements for numbers of sensor sites; and had contracted for weather forecasting services.
- The Washington Department of Transportation had contracted for road thermographic analysis and installed sensors in the Seattle area; had contracted for weather forecasting services for a number of areas in the state; and participated in a unique, multi-agency RWIS sensor system installation in the Spokane area.

Gathering information from these three states provided the ability to investigate the benefit-cost relationships and feasibility of nearly all of the forms of RWIS technologies.

BENEFIT-COST MODEL

There are many possible considerations for inclusion in a benefit-cost analysis for snow and ice control. There are indirect and direct benefits and, for the most part, only direct costs. Indirect benefits can be categorized as societal; snow and ice control practices can improve traffic flow, reduce fuel consumption, reduce accident rates, decrease insurance premiums, and so forth. Direct benefits include reduced expenditures for labor, equipment, and materials. The indirect costs are difficult to estimate and are controversial. Direct costs can be gleaned from records of expenditures for snow and ice control. To ensure a feasible level of effort and to maximize objectivity of the results, the decision was made to focus on direct costs. Benefits, then, would be reductions in direct costs.

Although one possible result of improved snow and ice control decision making is reduced costs, the other possibility is an improvement (or reduction) in the level of service provided to the traveling public. For the purpose of this study, level of service has been defined as what the highway agency does for snow and ice control. The research team decided that, at a minimum, any potential savings should not be at the expense of the traveling public, (i.e., a reduction in the level of service). Therefore, the methodology should also track the level of service provided in order to determine if it were degraded or not.

A computer model was developed that computes the costs associated with the allocation of snow and ice control resources and monitors the level of service provided by each allocation decision. Because the methodology deals with different snow and ice control strategies and different weather regimes, a statistical model was developed that uses the frequencies of occurrence of weather events and road conditions as a starting point. Cyrus G. Ulberg at TRAC, with considerable computer and benefit-cost experience and expertise, developed the model. The model is written in FORTRAN and runs on an IBM-compatible, 80286 or 80386 personal computer with a graphics card, 640 bytes of memory, and a mathematics coprocessor. Because the model was developed expressly for the analysis required in this project, it is not documented for general release.

Model Inputs

The model accounts for different snow and ice control practices. For example, in much of the country, especially the Northeast and Midwest, highway agencies use a great deal of chemicals, [e.g., sodium chloride (salt)], to remove snow and ice. Progressing farther west, proportionally less chemicals are used, although more abrasives are applied. The amount of salt used by state, based on survey results from this project, is shown in Figure 1 and the amount of abrasives used are shown in Figure 2. States where "No Data" is shown did not respond to the survey. Each of the practices has its own effectiveness, cost, and associated weather-related thresholds for decision makers. The model needed to be flexible enough to include those variations.

Additionally, the climate varies greatly from east to west and from north to south. The benefit-cost analysis includes evaluations of practices in different climates. Standard climatological data available from local National Weather Service forecast offices were selected as the best descriptors of climate for each area analyzed. These climatological summaries provide the frequency of occurrence of weather phenomena on a monthly basis. The weather phenomena used in this analysis include the frequency of occurrence of snow or ice, rain, and fog (for frost formation). It was assumed that the winter season runs from October through March; the frequencies were summed over that period to get a seasonal frequency of occurrence.

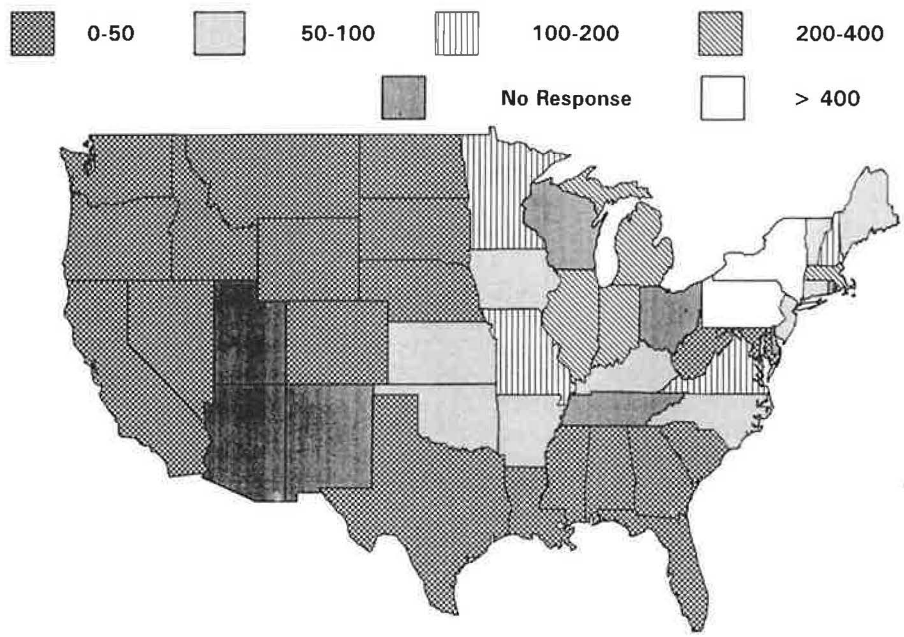

FIGURE 1 Annual salt usage by state for snow and ice control (in thousands of tons).

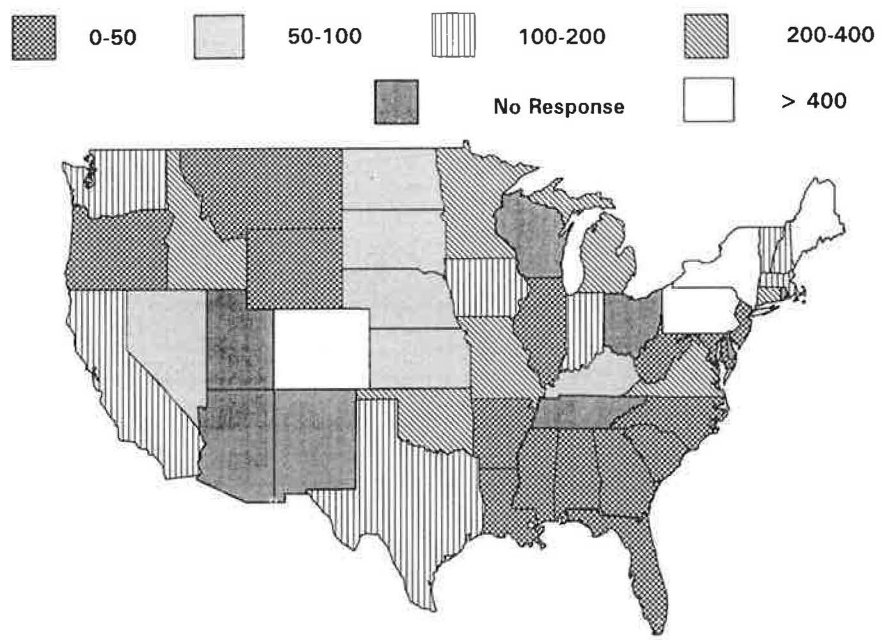

FIGURE 2 Annual sand usage by state for snow and ice control (in thousands of tons).

However, highway maintenance decision makers react to the condition of the road as well as to the weather. Also, the climatologies described above refer to specific points, namely the airports from which the meteorological measurements are taken. The road conditions can vary considerably in a small region because of many influences, such as the presence of water, topography, orientation of a road toward the sun, cuts, and other exposure considerations. For example, if it is snowing at the airport, there may be a distribution of road conditions varying from dry, to snow-covered, to wet. As a result, the model was designed to provide a distribution of road conditions over a road network, based on the climatological input.

The purpose of the model is to generate costs of snow and ice control actions taken based on the weather and pavement condition information available to the maintenance manager. The assumption used in constructing the model is that the maintenance manager will make the correct decision based on the information at hand. That information will vary as a function of the type of information used. The flow of information that generates the output is shown in Figure 3.

The first piece of information generated by the model is a weather event. The model uses a random number generator applied to the climatology distribution. Over a large number of iterations, the model will also generate the climatology of events because the random number generator will generate an even distribution of numbers from 0.0 to 1.0. How a frequency distribution of weather events is generated by using a computer's random number generator is shown in Figure 4.

The weather event is used to produce the road conditions to which the maintenance managers react. In the example of "No Significant Weather" already described, the road segments will have been given "ice," "snow," "clear," or "wet" conditions, based on the climatology or road conditions. Once a road condition is specified, another routine produces the weather information the maintenance manager uses to decide

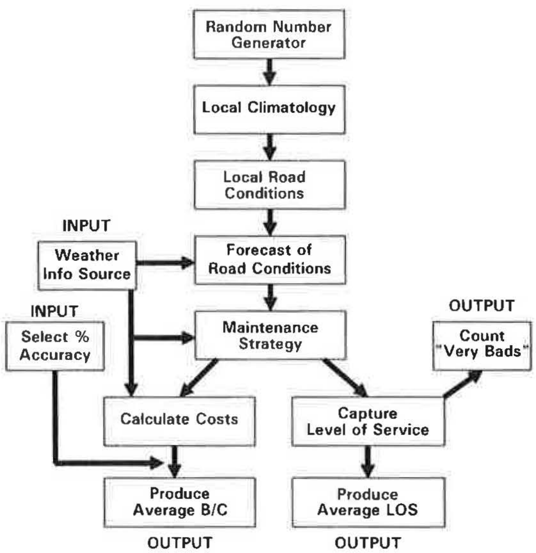

FIGURE 3 Flow of information in the benefit-cost model.

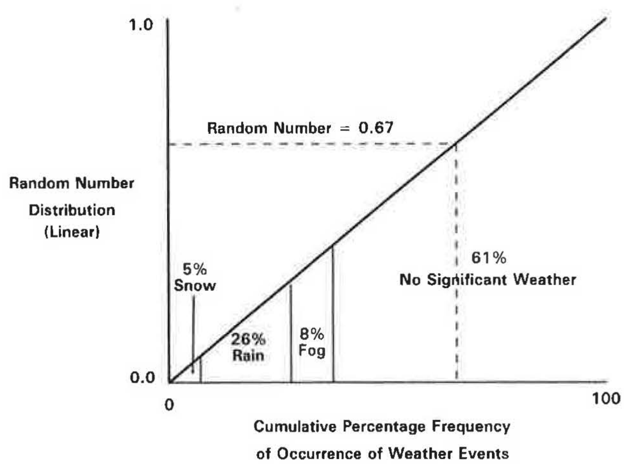

FIGURE 4 Example of generating a weather event.

to allocate snow and ice control resources. Based on the selection of the source of RWIS information, an action is selected. Each action has an associated cost and a level of service.

Once the decision is made on what resources to mobilize, the model captures the cost of the resource allocation and the level of service attached to the action. The level of service is rated on a subjective scale of 1 to 5, 1 being best and 5 being worst. If roads are dry, then any maintenance action selected is a "1," but has a cost associated with it. On the other hand, if the road is icy and the forecast was for "wet" and no action was taken, then the level of service would be "5."

At this point, the model has generated a cost and level of service for a specific maintenance action. This cost and level of service is then compared with the actions selected based on different weather information, in order to determine the benefit-cost ratio for the analysis. As more and better information is made available to the maintenance manager, the better is the decision that can be made. A typical scenario would be for the maintenance manager to get weather information from the media. The decisions made with that information are then compared with decisions that were made based on detailed forecasts and interaction with a forecaster for the weather and road conditions at specific locations. The costs of each action are compared, and a benefit-to-cost ratio is computed based on the costs of the maintenance actions and the costs of the information used to make the decisions.

In order to calculate the benefit-cost ratio (B/C), the model must be run for a number of iterations in order for a B/C to converge. At every hundredth iteration the model computes how many iterations are required to have either 2 or 5 percent accuracy in B/C at the 95 percent confidence levels. In some cases, the number of iterations required for a 2 percent accuracy was extraordinarily high; therefore the B/C is computed at least to the 5 percent accuracy level with 95 percent confidence. This appears very adequate because the computed B/C is usually much greater than 1. If the B/C were close to 1, increased accuracy might be desired.

Model Matrices

All of the information used in the model is contained in matrices of information. Each element of a matrix is a number (value) that is assigned to a piece of information (name). This section explains the matrices used in the model.

One-Dimensional Matrices

The one-dimensional matrices are lists of names that have values assigned to them. They are one-dimensional because there is one list of names, each with a value assigned. These matrices include the climatology of weather events, the costs of snow and ice control resources, and the costs of weather information technologies.

The climatology of weather events is nothing more than the list of possible winter weather events that can be extracted from standard climatological summaries for a location, and their frequencies of occurrence. A climatology input matrix is shown in Table 1.

TABLE 1 Sample Climatology for Input to Benefit/Cost Model

Weather Event (Name)	Frequency of Occurrence (Value)
No significant Weather	0.61
Rain	0.26
Snow	0.05
Fog	0.08

The second one-dimensional matrix contains the snow and ice control resources and their associated costs. Resources include people such as equipment operators; vehicles such as pickup trucks, trucks with spreaders, and trucks with plows; and materials such as abrasives and deicing chemicals.

The third one-dimensional matrix is the list of weather information technologies to be used in the decision process and their costs. These could include information obtained from media sources, in-place meterological and pavement surface sensors, detailed forecasts from private meteorological services, road thermography, and combinations of these technologies. Each technology has a cost assigned based on the prices being paid by the highway maintenance agencies. The cost is reduced to a daily rate. Technologies having a one-time cost use a daily rate calculated by amortizing costs over 5 years and 180 days of winter per year.

Two-Dimensional Matrix

The benefit-cost model employs one two-dimensional matrix. This matrix assigns the snow and ice control resources to a maintenance strategy. It is this matrix that generates the costs. The costs of resources assigned are based on the assumption that the snow and ice control activity (strategy) will require 8 hr, and that the resources must deal with 100 mi of four-lane highways during that 8-hr period. Examples of resources for one strategy could be three people driving three trucks with spreaders applying chemicals at the rate of 300 lb/lane-mile for an ice event, one person driving a pickup truck for winter patrolling, or combinations of these.

Three-Dimensional Matrices

Four three-dimensional matrices are used in the model. The first is used to distribute road conditions over the road network. Because each model calculation is initialized by climatology, the first number produced is a weather condition. However, actions are taken based on road conditions. This matrix uses local knowledge to estimate a frequency of occurrence of road conditions because there is no "climatology of road conditions." For example, in an area, if snow is occurring at the airport reporting station, there is likely to be snow on some roads, whereas others may be wet or even dry. The values in the matrix are the frequency of occurrence of a road condition given that a weather condition is specified (two dimensions). The third dimension of the matrix is the road segment. Being able to specify the road segment allows for making some roads more troublesome for snow and ice control (i.e., more snow, more ice, or more frost).

The second three-dimensional matrix generates the weather information that is used in the resource-allocation decision process. This matrix assigns the probability to the forecast (two dimensions). For instance, if the road condition generated from the matrix above is "snow," then the likelihood that snow was forecast to accumulate on the road might be 0.75 from a meteorological service. The third dimension of the matrix is the weather information source. The maintenance manager could also have based a resource-allocation decision on information heard over media, National Weather Service forecasts, pavement temperature sensors, and so on. Because the benefit-cost methodology assumes that the resource allocations for snow and ice control are based on information received, this matrix is used with the next one to generate the strategies for which costs are calculated.

The third three-dimensional matrix generates the snow and ice control action. If a road condition is forecast, a resource-allocation response occurs (two dimensions). For example, if the expected road condition is "snow," then snowplows are called for; if only wet roads are expected, no action would be the appropriate response. The values in the matrix are either 0 or 1. A 1 selects the strategy for the specified road condition forecast; all other elements of that row are 0. Only one strategy can be selected for a given road condition. The third dimension of this matrix is again the source of the weather information. It is assumed that changes in assigning resources will result based on the information source: normal procedure in one maintenance area might have been to use nightly winter road patrols; with detailed forecasts of road conditions available, the routine patrolling can be discontinued. Simple three-dimensional (2 × 3 × 2) matrices for this scenario are shown in Figures 5 and 6.

The last three-dimensional matrix assigns a "level-of-service" value to the response strategy for a given road condition. The values range from 1 (very good) to 5 (very bad), and are assigned based on a subjective hierarchy that was established

MAINTENANCE STRATEGY

FORECAST CONDITIONS		No Response	Patrol	Truck + Plow
	No significant Weather	0	1	0
	Snow	0	0	1

FIGURE 5 First-level weather information source: media.

MAINTENANCE STRATEGY

FORECAST CONDITIONS		No Response	Patrol	Truck + Plow
	No significant Weather	1	0	0
	Snow	0	0	1

FIGURE 6 Second-level weather information source: detailed forecasts from a private service.

for this model. For example, "very good" to "good" would be assigned to any strategy selected when the roads are dry; "very bad" would be assigned to doing nothing when snow or ice is expected to accumulate on the roads. In between might be a 2 or 3 for implementing chemical applications for ice in a timely fashion, to a 4 for doing the same thing as a reactive measure. This matrix allows the model to keep track of the average level of service in order to make the comparisons between weather information technologies. The model also counts the number of 5 occurrences. The level-of-service matrix is constructed using 5 to reflect Type I errors, the errors that occur when someone should have taken action, but did not. The purpose of monitoring the Type I errors is to determine the effectiveness of the RWIS information source in reducing Type I errors.

During early model runs, it was discovered that the costs of snow and ice control responses were not being valued properly. If taking no maintenance action was selected because of bad information and the roads were icy or snow-covered, the level of service would reflect a "very bad," but there would be no cost associated with doing nothing. In order to correct this discrepancy, new response strategies were devised that simulate what really happens. If resources are not mobilized in a timely way for snow situations, it usually takes longer to remove the snow. Similarly, if chemicals are not applied quickly, ice or snow situations can take longer to mitigate. Each of these situations provides a reduced level of service and costs the highway agency more. Strategies were devised and resources assigned to capture the additional costs of incorrect decisions. The model in its present form also has the capability to include additional societal costs. No attempt is made to include those costs because they are too difficult to quantify.

Model Results

Simple scenarios were created to gain an understanding of the model. These included developing a one-segment road network 100 mi long; creating simple two-element matrices of climatologies, weather information strategies, resources, and actions; and building 2 × 2 matrices for all of the other inputs.

An example scenario contained a climatology of snow-no snow, weather information from a forecasting service versus media-only information; and response strategies that included a winter patrol in use with media information versus no patrol and snowplow response with forecast service, as already described. The values assigned to the names in the matrices were varied in order to conduct an analysis of the sensitivity of the model to various inputs. This also included an initial look at using perfect forecasts for setting a limit to the benefit-cost ratio.

These initial results showed that the B/C varied inversely with the frequency of occurrence of "bad" weather. A possible explanation for this is that there is little chance to make a wrong decision if it snows every day. However, if snow is an infrequent occurrence, then erroneous decisions can be very costly.

Additionally, the early results pointed out that any increase in forecasting ability over chance (50-50 guess) produces a high B/C (> 10.0). This was because of the baseline scenario in which road patrols are used without forecasting support and are not used with the forecasting support. Reducing the overhead of road patrols provides a large savings. Also, the cost of a weather forecasting service is very small when compared with the costs associated with snow and ice control activities.

Following the initial familiarity runs of the model, scenarios were developed for each of the three states previously described. Matrices were built that reflected each state's snow and ice control practices, potential weather information sources, climatologies, and characteristic road condition distributions. The following sections describe the general results of the model as applied to scenarios that more closely represent reality.

Forecasting Support

In all cases, model runs show a high B/C (> 20.0) when decisions are made proactively using forecast support when compared with no forecast support. Even a slight improvement in decision making based on typical costs of private meteorological services as compared with media information shows a significant cost savings and high B/C. A cost of $25/day for forecasting services for a small area was used. This was an average of known contracting costs with an added daily communications cost. These costs are somewhat deflated currently because of competition and frequent low-bid contracting by highway maintenance agencies. The consequence of the lower cost, however, may be reduced meteorological support in terms of the quantity and quality of the information provided to the decision maker. The model shows, however, that if the costs of private meteorological services are increased as much as tenfold, the B/C is still greater than 1.0. In addition to the high B/C, the level of service (reduced bad decisions) improved markedly.

RWIS Hardware

The data available to maintenance managers from RWIS sensors typically include pavement temperature, air temperature, relative humidity, wind speed and direction, pavement condition (wet, dry, icy) and an indication of the amount of deicing chemicals on the surface. These data can be used to monitor the potential for ice or snow bonding and frost formation. Sensor data tend to provide information to which a maintenance manager can only react. However, with the wealth of experience most maintenance managers have—which can be supplemented by sensor information—the manager can frequently make timely resource allocation decisions. These can include not implementing snow and ice control because sensors indicate that the pavement is too warm for snow or ice bonding, or that sufficient chemicals remain on the road surface to warrant no response, or that plowing only, without chemicals, may be appropriate.

RWIS sensor systems can cost as much as $40,000 per location. For instance, five sensors systems located over the 100-mi network of roads used in the model, plus a central computer and workstations needed to process data, can easily put the cost of a sensor system at more than $250,000. Amortized over 5 years and 180-day winters, the daily cost can exceed $300. In each of the three states used in this investigation, the number of sensors in an area varies. Actual daily costs varied by location: Washington, $222; Colorado, $500; and Minnesota, $350, based on a recent procurement action for additional systems. In the scenarios developed, and with the subjective input of the marginal improvement possible in road condition forecasting with sensors compared to media information, the B/C calculated were small, and ranged from −1.5, where the increase in cost of the RWIS technologies exceeds the decrease in direct maintenance costs, to very close to 1.0. This shows that sensors alone are not the answer to saving costs of snow and ice control practices.

Road Thermography

Very little road thermography has been conducted outside Europe. Only Wisconsin, Washington, and Minnesota had thermal profiles made of some of their highways. There is, in general, little experience in the snow and ice control community using road thermography to assist snow and ice control decision makers. Such data also have little value by themselves for resource allocation decisions. In addition, the temperature profiles are cumbersome to use. In theory, if a pavement temperature is available for a given point, then with road temperature profiles, an estimate of road temperatures elsewhere can be made. Washington has been evaluating this capability and has demonstrated some success. Little if any change can be made to snow and ice control decision processes using temperature profiles by themselves, however.

Analysis of road thermography data conducted in this project does indicate such data have applicability in conjunction with other pavement condition information, such as pavement temperature forecasts for a specific location, particularly where there is a large range of pavement temperatures. This also implies that some measure of improved proactive decision making can be obtained in this manner. For instance, only certain spots may need attention during a snow or ice weather event.

During interviews conducted as a part of this project, it was found that road thermography data had allowed snow and ice control managers to revise plowing routes to capture the coldest segments first. The data also showed that some structures remained warmer than surrounding road surfaces, and where the maintenance forces had been treating the bridges first, they reversed their priority. There are potential cost savings in these types of decisions. Other savings may be possible by using such data to assist in the placement of sensor systems. Potentially, the daily cost of sensor systems can be reduced by decreasing the number of sensor systems in place. That can be a significant improvement in the B/C for this technology.

Although the price tag for road thermography appears high, it is because it is a one-time, up-front cost. If the cost of the thermographic analysis is amortized over the same 5-year, 180-day winter period, the cost is not much different from the private meteorological support on a daily basis. In the Washington state scenario, using the model with an assumed 5 percent increase in forecasting skill, the B/C also increased about 5 percent, even though the cost of the weather information increased with the added cost of road thermography.

Sensors, Road Thermography, and Forecast Support

There is no single weather information technology that will approach the ability of detailed, local forecasts of road conditions in terms of B/C. Sensor systems by themselves are costly, but provide some increase in decision-making capability. They can provide information for analysis, such as temperature trends, roadway deicing chemical concentrations for taking or not taking action, and icing conditions in particular locations. Road thermography provides little information on its own for decision making. However, there is a synergistic relationship when these technologies are combined. Each allows a meteorological services provider to produce more accurate forecasts. This in turn allows for more efficient and timely snow and ice control decisions. For the combined technologies, the model produces a B/C of approximately 5.0. However, the model also shows a significant increase in the level of service with the combined technologies. Average computed level of service improvements were on the order of 20 percent. An even larger reduction in the number of Type I errors is made possible, with reductions by as much as 90 percent.

CONCLUSIONS

The benefit-cost model previously described shows that the use of road weather information technologies can significantly reduce the costs of snow and ice control. Using weather and pavement condition forecasts proactively to mobilize snow and ice control resources ahead of snow and ice problems, and to not mobilize or patrol when it is not necessary, saves money. Similarly, deploying resources in a timely and efficient way and at the right location also provides a better level of service to the road users.

The greatest benefit-cost ratios are produced by using weather and pavement condition forecasts. B/C > 20.0 result from the low cost of forecast services when compared with the cost of snow and ice control activities. In addition, the model assumes that the maintenance manager always makes the right decision when presented with the weather and pavement condition information. This is an idealistic scenario, given the general conservative nature of maintenance managers who would rather err on the side of safety. It also assumes that perfect communication takes place between the forecast provider and the forecast user. However, the model indicates that tenfold increases in the cost of such services still provide a positive return on investment. It also shows that using winter safety patrols is a costly practice; reliable forecasts can help reduce the costs of snow and ice control significantly if patrols can be eliminated or reduced.

Calculations of benefit-cost ratios using information from sensor systems and road thermography by themselves are significantly lower than those that also use a detailed weather and pavement condition forecast support system. In fact, use of these technologies singly may cost more than they save without forecast support. On the other hand, they can improve the level of service. The model can be used, however, to assess what the maximum expenditures for weather information could or should be in an area by varying the costs of the RWIS technologies.

Sensitivity analysis shows that low B/C results are likely in severe climates (i.e., having many snow and ice problems). The reason is that there are fewer decisions to make when snow or ice happen most of the time. This same reasoning would argue that RWIS support is less likely to provide a great deal of savings when maintenance managers deploy snow and ice control resources throughout the winter in multiple shifts, unless they decide to mobilize with each snow or ice situation. There could be significant savings for these managers, however, in the spring and fall transition seasons, when resources are deployed less regularly.

The benefit-cost model developed for this project shows that through the use of road weather information technologies, the costs of snow and ice control can be reduced. The greatest single savings is possible through the use of detailed weather and road condition forecasting support. The inclusion of road weather information system sensor technology, and the use of road thermography with the forecasts, which result in a reduced benefit-cost ratio, will significantly improve the snow and ice control level of service and will reduce the Type I errors of omission.

REFERENCE

1. *Highway Statistics—1987.* Federal Highway Administration, U.S. Department of Transportation, 1987.

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