

*NDOR Research Project Number S-STWD(1033)
Transportation Research Studies*

**GUIDELINES FOR PRIORITIZING BRIDGE DECK
ANTI-ICING SYSTEM INSTALLATIONS**

**PHASE I: DATABASE CREATION
AND
PRELIMINARY DATA ANALYSIS**

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Prepared for

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EXECUTIVE SUMMARY

This report presents information on Phase I of the Research Project Number S-STWD(1033) titled “Guidelines for Prioritizing Bridge Deck Anti-Icing System Installations.” During severe winter conditions, bridges freeze before the surrounding roadways – often catching unsuspecting drivers off guard. Depending on weather and pavement conditions, automatic bridge deck anti-icing systems spray chemicals that prevent or minimize ice bonding to the pavement. The Nebraska Department of Roads (NDOR) is interested in installing such systems on various bridges statewide. However, limited funding requires that bridges be prioritized for installation based on relevant criteria.

During Phase I, the research team conducted a review of pertinent literature on automatic bridge anti-icing systems and the experience reported by various transportation agencies. Several factors considered in the decision to install automatic anti-icing systems were identified. These factors included accident history, bridge alignment, weather, traffic, and bridge distance from maintenance yard, among others. A methodology to build a database of relevant factors and a decision-making module in geographic information system (GIS)/spreadsheet environment was developed.

Database construction involved merging information on factors, deemed important in the prioritization of bridge deck anti-icing system installations, from several sources. These sources included NDOR bridge inventory, NDOR accident database, archived weather data from the High Plains Regional Climate Center, Nebraska streets database, Nebraska rivers and streams database, and NDOR maintenance yard information.

The decision-making module provides a user-friendly interface through which users can provide input needed for bridge prioritization. This module incorporates four different decision-aid formats; namely benefit-cost ratio, cost-effectiveness, utility index, and composite programming. Users may obtain alternative guidelines depending on the chosen format. The benefit-cost and cost-effectiveness formats are based on single-criterion optimization, whereas the utility index and composite programming formats are based on multi-objective analysis. The first two formats maximize the benefit and safety improvement per unit cost associated with the installation of automatic anti-icing systems, while the last two formats seek the best possible compromise solution among several conflicting objectives.

A prioritized list of 26 bridges was received from NDOR. The priority of this list was based on the number of accidents reported during icy and snowy conditions. These 26 bridges were prioritized in the decision-making module using all formats. Bridge prioritizations from benefit-cost and cost-effectiveness formats were similar and those of the utility index and composite programming formats were similar. However, prioritizations in all four of these lists were different than the NDOR prioritized list. Reasons for different rankings in the five lists were due to differences in the criteria and weighting factors used in the prioritization process.

Given the flexibility and suitability of the composite programming format to bridge prioritization and its advantages over other methods, it appears to be the most suitable for further development in Phase II of the project. Other tasks recommended for Phase II that will aid NDOR in making better decisions include: development of appropriate weights for use in the composite programming format, study of automatic anti-icing systems already installed in Nebraska to collect Nebraska-specific data, development of an interface between the database and decision-making modules, and development of a user guide and on-site training for NDOR personnel.

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INTRODUCTION

1.1 BACKGROUND

Severe winter weather creates hazardous driving conditions that invariably lead to increased vehicular accidents. One of the major problems is the freezing of moisture on bridge decks, which occurs well before moisture freezes on the rest of the roadway surface. Unsuspecting drivers are often caught off guard and lose control of their vehicles while traveling over frozen bridge decks, leading to the unfortunate consequences of traffic accidents.

Some states have successfully used bridge deck anti-icing systems, which automatically apply deicing liquid chemicals to bridge decks when icing conditions are detected. Thus, these systems prevent moisture from freezing and bonding to the bridge deck. The Nebraska Department of Roads (NDOR) district offices have proposed several installations of bridge deck anti-icing systems. However, highway funds are not sufficient to install these systems at all of the proposed locations. Therefore, a method of prioritizing bridges for the installation of anti-icing systems is needed to facilitate the most cost-effective deployment.

1.2 OBJECTIVE

The objective of this research is to develop a method for prioritizing bridge locations for installation of automatic bridge deck anti-icing systems. The method will facilitate the most cost-effective deployment of these systems in Nebraska. Besides the method, an initial prioritized list of bridge locations will be developed for NDOR.

1.3 CONTENTS OF REPORT

This report documents the results of Phase I of NDOR Research Project Number S-STWD(1033) titled “Guidelines for Prioritizing Bridge Deck Anti-Icing System Installations,” which is being conducted by the Mid-America Transportation Center at the University of Nebraska-Lincoln. Pertinent literature on winter snow maintenance and automatic anti-icing systems is summarized in Chapter 2. The methodology adopted for this research, the database construction, and the alternative decision-aid formats are described in Chapters 3, 4, and 5, respectively. The

alternative decision-aid formats are compared in Chapter 6, and the Phase I conclusions are presented in Chapter 7. The recommended Phase II work plan is outlined in Chapter 8.

LITERATURE REVIEW

2.1 WINTER MAINTENANCE STRATEGIES

Agencies can adopt either reactive or proactive winter maintenance strategies for roadway clearance during winter snow conditions. The reactive strategy consists of deicing procedures, which involve plowing and application of deicing chemicals (water freeze point depressants) to the roadway after accumulation of a predetermined amount of snow. Examples of deicing chemicals include sodium chloride, magnesium chloride, calcium chloride, and potassium acetate. The reactive nature of this strategy allows the formation of a compacted snow layer on the road surface. This layer tightly bonds to the surface due to traffic load and requires a large amount of deicing chemical to penetrate the layer and break the bond (C-SHRP, 2000).

The proactive strategy consists of anti-icing, which is the practice of preventing the formation or development of bonded snow and ice by timely applications of a freezing-point depressant (Ketcham et al., 1996). According to Hogan (2001), anti-icing of highways has been in use since the late 1930's. The application of granular sodium chloride during the early stages of a snowfall began around 1938. A report by the SHRP Anti-Icing/RWIS Lead States Team (2000) indicated widespread (90 percent of the responding agencies) use of anti-icing in both the United States and Canada. Sodium chloride and magnesium chloride were found to be the most common deicing chemicals. Compared to deicing, some of the advantages of anti-icing include: enhanced traffic safety during winter storms, potential savings for the same level of service, and minimized environmental impact resulting from the reduction of chemicals used for snow clearance (C-SHRP, 2000). In a National Cooperative Highway Research Program (NCHRP) sponsored study, Boselly (2001) reported that several state transportation agencies have successfully implemented anti-icing programs and have documented considerable savings. Boselly (2001) concluded that anti-icing reduces cost of providing a specified level of service, saves 10 to 20 percent of an agency's snow and ice control budget, and increases safety for the traveling public through accident reduction.

2.2 AUTOMATIC ANTI-ICING SYSTEMS

Automatic anti-icing systems spray deicing chemicals on a roadway or bridge deck from nozzles installed in the pavement or bridge parapet/railing. These systems are usually used in conjunction with a Roadway Weather Information System (RWIS), which provides the needed decision-making information regarding spray timing. Several studies have documented the benefit-cost analyses of automatic anti-icing systems. A study by Stowe (2001) indicated a benefit-cost ratio of 2.36 and a net benefit of \$1,179,274 for an automatic anti-icing system. The Minnesota Department of Transportation (MnDOT, undated) reported on three automatic anti-icing system installations in Minnesota: Interstate 35 Bridge near Duluth, Truck Hwy 61 Bridge near Winona, and an intersection in Dresbach. MnDOT reported accident reductions of 56, 100, and 100 percent at the Duluth, Winona, and Dresbach locations, respectively. Benefit-cost ratios of 2.0, 3.1, and 2.7 were reported for these three locations. Another Minnesota-based study by Johnson (2001) evaluated the I-35W and Mississippi River Bridge anti-icing system. The evaluation indicated a reduction of 68 percent in the number of winter season accidents on the bridge and a benefit/cost ratio of 3.4.

The German Federal Road Research Institute documented safety benefits from the installation of automatic anti-icing systems (Bundesanstalt für Strassenwesen, 1993). The agency reported that after installation of an automatic system, the number of accidents was reduced by more than 50 percent. Specifically, an 85-percent reduction was observed for accidents with light injuries, 65-percent reduction in accidents leading to material damage, and 25-percent reduction in accidents with heavy material damage. After comparing total costs to total benefits, a profitability factor of 1.88 was reported by the agency.

Barrett and Pigman (2001) evaluated an automatic bridge deck anti-icing system installed on southbound I-75 at the North interchange to Corbin, Kentucky. After four winter seasons, the system had minimal problems and worked efficiently. However, the system's effectiveness was limited by its location. Being on an interstate, the bridge was part of winter maintenance activities anyway, and it was located in a part of the state that does not receive abundant precipitation. The authors recommended that the system be used in the following places: (1) accident-prone areas, (2) isolated bridges that require deicing trucks to travel an unreasonable distance to treat, (3) remote areas that are difficult to reach in bad weather, and (4) bridges over water, which may be more susceptible to freezing moisture.

Finally, NDOR conducted a survey (unpublished) to assess automatic anti-icing system usage among state transportation agencies and to determine the existence of any criteria and guidelines for deploying such systems. Of the 19 agencies that responded to the survey, only eight (42 percent) indicated they either use or plan to use automatic bridge deck anti-icing systems. Only two (10.5 percent) state agencies (Maryland and Wisconsin) indicated that they have prioritization guidelines for the installation of such systems. Major criteria used by Wisconsin include: accident history, bridge grade, locations susceptible to black ice or frost, super-elevated decks, average daily traffic (ADT), distance from the nearest salt stockpile, potential for moisture generation, high winds, and bridge span. The NDOR survey asked respondents what criteria would they use for prioritization of bridge locations. Some of the frequently cited criteria were accidents, bridge distance from maintenance yard, and weather. Finally, a number of respondents indicated their interest in the findings of the NDOR survey because of the importance of the topic to them.

2.3 SUMMARY

Overall, the literature review indicates that anti-icing is a proactive strategy that can effectively be used for improving highway safety during snowy and icy conditions, while realizing cost savings and environmental benefits. Several studies indicate the economic viability of automatic anti-icing systems. The benefit-cost ratios of such systems are in the range of 1.8 to 3.4 and accident frequency reduction varies from 25 to 100 percent. However, benefits from these systems are location-dependent. Very few state transportation agencies have guidelines on prioritizing bridge locations for installation of automatic anti-icing systems. Some of the important factors in bridge prioritization include accident history, bridge alignment, weather, and distance from maintenance yard.

Chapter 3

METHODOLOGY

The methodology developed in this research for prioritizing bridge anti-icing system installations is shown in Figure 1. It consists of two modules: database and decision-making. In the database module, information from several sources was combined in a Geographic Information System (GIS) environment. The combined information was used to create two databases, an accident database and a bridge database. State traffic accident data were combined with weather and bridge inventory information to obtain accidents that occurred under wet or snowy conditions on or within 300 feet of either end of each bridge on the state highway system. To create the bridge database, information was combined from the following sources:

- NDOR bridge inventory,
- NDOR traffic data,
- NDOR maintenance yard information,
- High Plains Regional Climate Center,
- Nebraska street database, and
- Nebraska rivers and streams database.

Details of construction of the accident and bridge databases are given in Chapter 4.

The accident and bridge databases in the database module were then input to the decision-making module. This module was developed in a spreadsheet environment. It uses the four alternative decision-aid formats (benefit-cost, cost-effectiveness, utility index, and composite programming) to analyze the data and generate a prioritized list of bridge deck anti-icing system installations. As described in Chapter 8, in Phase II of this research, the decision-making module will be coupled with ArcView GIS software to provide geographical displays of the module's output.

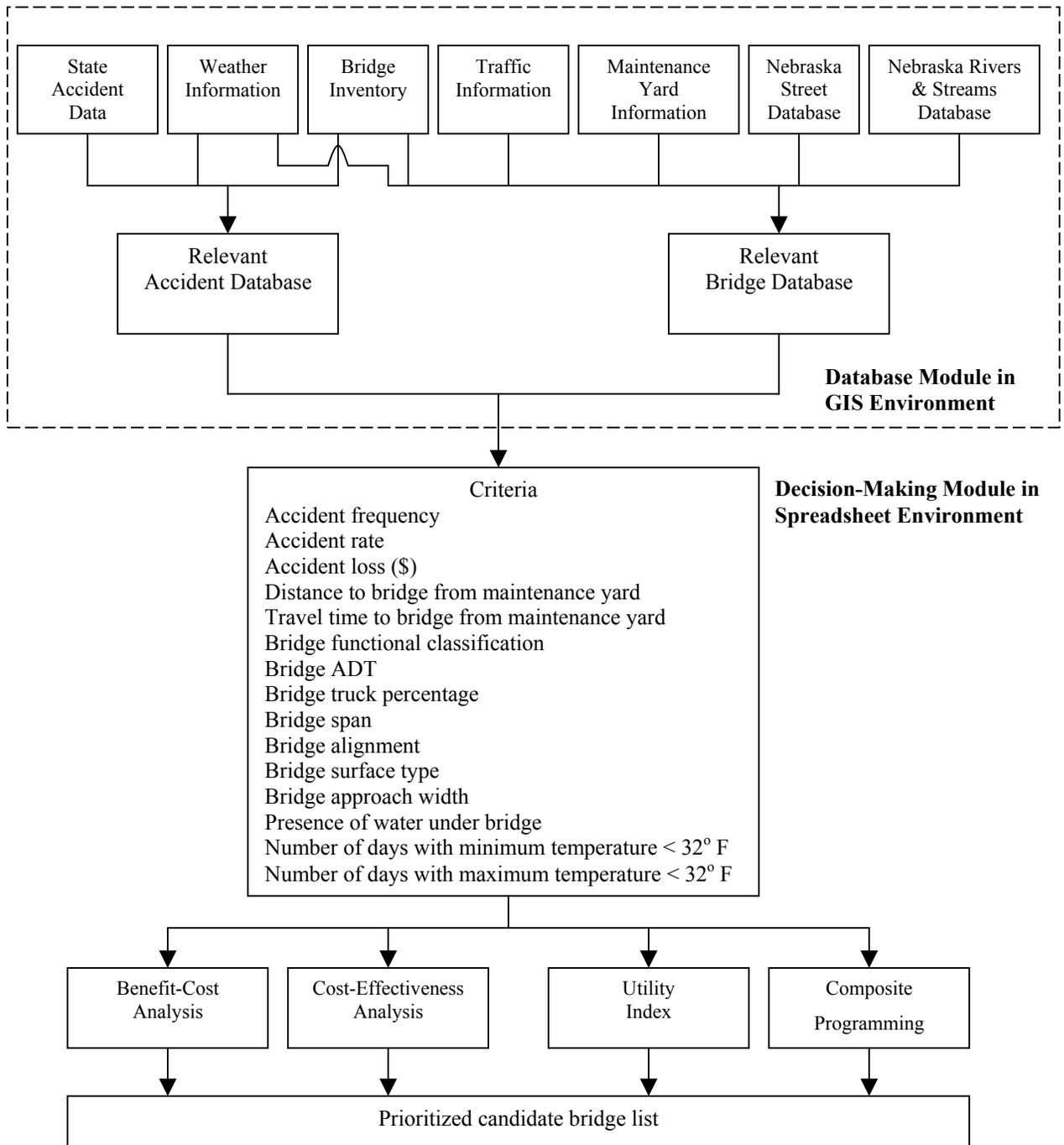


Figure 3.1 Prioritization Methodology

Chapter 4

DATABASE CONSTRUCTION

As described in Chapter 3, information from a variety of sources was gathered for the construction of the accident and bridge databases used in the methodology. A description of each source, its contribution, and the process to extract necessary information from it is presented in this chapter. Details of merging information from individual sources are given at the end of this chapter.

4.1 ACCIDENT DATA

The accident data were provided by NDOR for the 13-year period from 1988 to 2000. The data included all reported accidents on or within 300 feet of either end of each bridge on the state highway system. Database attributes included several elements such as date of accident, surface conditions, route number, and injury severity. An accident severity database was created from these data by spatially joining bridge and accident data. Accidents that did not happen on or in the immediate vicinity of bridges were excluded from the analysis. Accidents by injury level (injury measured on the KABCO scale – Killed, A-type injury, B-type injury, C-Type injury, and Property-Damage-Only) were summarized for each bridge. This resulted in the generation of information on accidents involving different types of injuries for each bridge structure.

4.2 WEATHER INFORMATION

Archived Nebraska weather data for the 13-year study period (1988-2000) were obtained from the High Plains Regional Climate Center at the University of Nebraska-Lincoln. The weather data contained information on daily average maximum air temperature, minimum air temperature, precipitation, and snow amount from 316 weather stations located throughout Nebraska. The accident data from NDOR did not contain information on temperature. To find the approximate temperature at each bridge at the time of each accident, a 25-mile radius boundary was drawn around each bridge. Weather stations located within the respective boundaries for each bridge were used in estimating the temperature at the bridge location. The 25-mile radius was selected in order to ensure that each bridge had at least one weather station for temperature estimation. Based on date of accident, bridge location, and weather data, the average maximum temperature, minimum temperature, precipitation, and snowfall were found for each bridge location for the days that accidents occurred on the bridge.

A bridge temperature database was created containing information on the number of days a bridge experienced freezing temperatures (below 32° F). For each bridge, all weather stations inside the 25-mile radius were selected. Using data from the selected weather stations, the temperature data were interpolated for each day over the 13-year period. This allowed calculation of the total number of days when the maximum temperature was less than freezing and the total number of days when the minimum temperature was below freezing. Note that the temperature found by this process is actually air temperature and not bridge-deck temperature. In reality, the bridge-deck temperature may be different than the surrounding air temperature. However, bridge-deck temperature data were not available for Phase I of this research.

4.3 BRIDGE INVENTORY

Bridge data provided by NDOR contained the following information about each bridge on the state highway system:

- Structure number,
- route number,
- location (latitude and longitude),
- functional classification,
- length of bridge,
- average daily traffic (ADT) including truck percentage,
- approach roadway width,
- alignment,
- age, and
- wearing surface.

The bridge and accident databases were spatially joined and summarized based on bridge structure number to find the accident frequency and rate for each bridge. The frequency and rate of accidents associated with snowy, icy, or frosty surface conditions were calculated for each bridge. While frequencies were calculated based on the total number of accidents on each bridge, the 13-year accident rate for each bridge was calculated as:

$$AR = \frac{\sum T}{\sum (A * L * D)} * 10^6 \quad (4.1)$$

where:

AR = 13-year bridge accident rate (accidents per million-vehicle miles),

T = number of accidents on or within 300 feet either side of bridge in study period,

A = average daily traffic (vehicles per day),

L = length of bridge span plus 600 feet (converted to miles), and

D = number of days when the minimum daily temperature in bridge vicinity was below freezing during the 13-year study period.

4.4 TRAFFIC INFORMATION

NDOR provided Year 2000 traffic data (ADT and truck percentage), which were used to construct the database. Reliance on Year 2000 traffic data for the calculation of accident rates for the past 13-year period results in underestimated rates, assuming that ADT increases over time. However, in the absence of more specific historical traffic data, it was necessary to use this approach in this phase of the research.

4.5 NEBRASKA STREET DATABASE

The Nebraska street database from Environmental Systems Research Institute (ESRI) at the University of Nebraska-Lincoln was utilized for street network and postal address information. By using the programming language available in ArcView called Avenue, the length for each link in the state highway network was calculated. Speed limits on network links were obtained by utilizing census feature classification codes. Based on the calculated link length and speed limit, travel time on each link was calculated.

4.6 MAINTENANCE YARD INFORMATION

NDOR maintenance yard data included the postal address of each maintenance yard in Nebraska. Using postal address information and the address matching capabilities of ArcView, maintenance yards were located appropriately in a GIS database. A map showing the service area of each yard was obtained from NDOR. This map was digitized and transferred to ArcView. The travel times and distances from each maintenance yard to each bridge in its respective service area were calculated using the maintenance yard locations, their respective service areas, the Nebraska street database, and bridge locations.

4.7 NEBRASKA RIVERS AND STREAMS DATABASE

The Nebraska rivers and streams geographic database from ESRI was utilized to determine the locations of rivers and streams in Nebraska with respect to the bridges on the state highway system. Using ArcView, the bridge database was overlaid on the rivers and streams database to identify bridges that have water flowing underneath them.

4.8 MERGE OPERATIONS

A single accident-bridge database was created in ArcView by spatially merging the accident and bridge databases. Since anti-icing systems operate during snowy or icy conditions, only accidents that occurred during these conditions were selected for analysis. The weather database with temperature information on the day of the accident was joined to the accident-bridge database using the accident date as the match key. From this combined accident-bridge-weather data, accidents that occurred either when the road surface condition was snowy, or when it was wet and the minimum temperature was below freezing, were selected for further analysis. This ensured that the database contained accidents that might have been associated with freezing conditions. The database was summarized based on bridge structure number so that each bridge contained the following information:

- route number,
- latitude and longitude,
- national functional classification,
- ADT,
- bridge span,
- approach roadway width,
- truck percentage,
- alignment,
- wearing surface/protective system,
- age, and
- number of accidents.

Additional elements were added to this summarized database by various procedures. This additional information included:

- Unit accident costs for computing the cost of the accidents, which occurred on each bridge. Table 1 presents the average costs for injuries of different severity in traffic accidents.
- Number of days at each bridge when the maximum daily temperature was below freezing.
- Maintenance yard and Nebraska street information for computing the travel time and distance from each bridge to its maintenance yard.
- Nebraska rivers and streams data for identifying bridges over bodies of water.
- Anti-icing system cost for each bridge, which was based on unit costs for a Nebraska bridge equipped with an anti-icing system.

Table 4.1 Unit Accident Costs*

Type of Injury	Description	Cost (\$)
K	Fatality	2,600,000
A	Disabling injury	180,000
B	Evident injury	36,000
C	Possible injury	19,000
0	Property damage only	2,000

* Source: The Traffic Safety Toolbox: A Primer on Traffic Safety. Institute of Transportation Engineers, 1999.

The addition of the above information to the summarized database completed the database creation process in ArcView. This database was then exported to the decision-making module, which was programmed in an MS Excel spreadsheet environment. The decision-making module in MS Excel has capabilities for user-defined input based on ADT and/or functional class. Users can input any value of ADT between 0 and 70,000 vehicles per day and any of the functional classification in Table 2 to limit the prioritization process to bridges within the specified ADT range and/or to bridges of certain functional classifications.

Table 4.2 Functional Classification

Classification	Description
20	All
Rural	
1	Principal arterial – Interstate
2	Principal arterial – Other
6	Minor arterial
7	Major collector
8	Minor collector
9	Local
Urban	
11	Principal arterial – Interstate
12	Principal arterial – Other freeways or expressways
14	Other principal arterial
16	Minor arterial
17	Collector
19	Local

ALTERNATIVE DECISION-AID FORMATS

Four alternative decision-aid formats were considered for prioritizing the installation of automatic bridge deck anti-icing systems. These were: (1) benefit-cost analysis, (2) cost-effectiveness analysis, (3) utility index, and (4) composite programming. The first two formats prioritize bridges based on a single-objective. The decision rule is to maximize the safety improvement or related cost savings per unit system costs. However, the last two formats prioritize system installations on the basis of multiple criteria. Since some of the criteria are conflicting, an optimum solution typically does not exist, and only a compromise solution can be sought instead. The four decision-aid formats are described in this chapter.

5.1 BENEFIT-COST ANALYSIS

Bridges can be prioritized based on the ratio of benefits generated from the installation of anti-icing systems and the associated costs. Bridges with higher benefit-cost ratios are given a higher priority for the installation of an automatic anti-icing system. However, the benefits and costs need to be quantified in monetary terms. The quantification of the benefits and costs of bridge anti-icing systems is described below.

5.1.1 Benefits

Benefits used in this analysis were the expected road user cost savings provided by an anti-icing system relative to the conventional de-icing procedures used in NDOR's winter operations. The two main components of road user costs are accident costs and the associated traffic delay costs (i.e., delayed traffic due to accidents).

The literature review indicated that installation of an anti-icing spray system reduces accident frequency by 25 to 100 percent. These figures are based on studies conducted in other states and countries. Accident reduction data associated with anti-icing spray systems installed in Nebraska are not available. Based on the findings of the literature review in Chapter 2, a 60-percent reduction in accident frequency for each injury level was assumed for the purpose of this analysis.

Accidents with five injury levels, based on the KABCO scale were considered. The estimated unit cost of accidents with different injury levels is shown in Table 4.1. Using these unit

accident costs, the expected accident cost savings (ACS) accrued from the installation of an anti-icing system can be computed as:

$$ACS = 0.60(C_k \sum K + C_a \sum A + C_b \sum B + C_c \sum C + C_{PDO} \sum PDO) \quad (5.1)$$

where:

$C_k, C_a, C_b, C_c,$ and C_{PDO} = costs in Table 1 for accidents with fatalities, A-type injury, B-type injury, C-type injury, and property damage only; and
 $\Sigma K, \Sigma A, \Sigma B, \Sigma C,$ and ΣPDO = number of accidents with fatal, A-type injury, B-type injury, C-type injury, and property damage only accidents at a bridge.

Avoided traffic delays due to fewer accidents would also constitute as benefits of an anti-icing system. Reductions in traffic delays would be a function of several factors including bridge traffic during adverse weather, accident characteristics (e.g., how many lanes are blocked), response time and efficiency of responding agencies (i.e., how soon the accident is cleared), and presence of alternate routes upstream of bridge. However, the data needed to compute the reduction in traffic delay were not available for Phase I of this research. Therefore, avoided traffic delays were not included in this analysis.

5.1.2 Costs

The cost of an anti-icing system depends on its capabilities and the bridge span, among other factors. Odin Systems International provided cost estimates for two different models of anti-icing systems, which are shown in Table 5.1. This information was subsequently used in the B/C analysis.

Table 5.1 Initial Cost of Automatic Bridge Deck Anti-Icing Systems

Model	Description	Cost (\$)
Odin Guardian	1000' bridge 2 lane roadway with 35 nozzles	56,675
	500' bridge 2 lane roadway with 15 nozzles	40,000
Odin Minuteman	1000' bridge 2 lane roadway with 35 nozzles	45,000
	500' bridge 2 lane roadway with 15 nozzles	27,000

These cost estimates were based on the assumption that system installation will be performed by the client agency. Otherwise, the total cost can be significantly higher. There are other variables in calculation of costs. For example, the addition of a single stand-alone pavement sensor increases the cost by \$7,500. System costs for bridges with different span lengths than those given in Table 5.1 can be estimated using the following equations, which were developed by approximate curve fitting of the data in Table 5.1:

$$\text{Odin Guardian} \quad C = -0.047 L^2 + 103L + 7500 \quad (5.2)$$

$$\text{Odin Minuteman} \quad C = -0.018 L^2 + 63L + 7500 \quad (5.3)$$

where:

C = system installation cost (\$), and

L = bridge span length (feet).

These equations include the cost of one pavement sensor for \$7,500.

The annual costs of each anti-icing system can be calculated as the annualized system installation cost using a 4-percent discount rate, a 10-year service life, and zero residual value. The annual operating and maintenance cost is approximately 5 percent of the installation cost.

5.2 COST-EFFECTIVENESS ANALYSIS

The cost-effectiveness analysis evaluates each bridge location based on the expected safety improvement per unit cost due to installation of an anti-icing system. The expected safety improvement of an anti-icing system is expressed in terms of a safety improvement index, SII. This index is a function of the expected reduction in accident frequency and severity. Using the same five KABCO injury levels that were considered in the benefit-cost analysis, SII can be calculated as:

$$SII = r_k \alpha_k \sum K + r_a \alpha_a \sum A + r_b \alpha_b \sum B + r_c \alpha_c \sum C + r_{pdo} \alpha_{pdo} \sum PDO \quad (5.4)$$

where:

$r_k, r_a, r_b, r_c, r_{pdo}$ = reduction factors for accidents with fatalities, A-type injury, B-type injury, C-type injury, and property damage only, respectively,

$\alpha_k, \alpha_a, \alpha_b, \alpha_c, \alpha_{pdo}$ = weights for accidents with fatalities, A-type injury, B-type injury, C-type injury, and property damage only, respectively, and
 $\Sigma K, \Sigma A, \Sigma B, \Sigma C,$ and ΣPDO = number of accidents with fatal, A-type injury, B-type injury, C-type injury, and property damage only accidents at a bridge.

Based on the literature review in Chapter 2, an accident frequency reduction factor of 0.60 was assumed for each accident severity level (i.e., $r_k = r_a = r_b = r_c = r_{pdo} = 0.60$). The proposed weights expressing the relative importance of accidents with different injury severity levels are summarized in Table 5.2. These values are proportional to the accident costs given in Table 4.1.

Table 5.2 Accident Severity Weights

Accident Severity	Description	Weight (α_i)
1	Fatality	0.9165
2	Disabling injury	0.0634
3	Evident injury	0.0127
4	Possible injury	0.0067
5	Property damage only	0.0007

The system cost is determined for each bridge based on the cost estimates given in the benefit-cost analysis. Then the safety improvement index SII is divided by the system cost, C, to determine the safety improvement index per unit cost. Finally, bridges are prioritized on the basis of the SII/C ratio. Installation of the automatic anti-icing spray system on bridges with higher SII/C ratio will have higher priority.

5.3 UTILITY INDEX

The method of utility index is among the most commonly used comparative evaluation procedures (Goicoechea et al., 1982). Let $\{\alpha_i: i=1, \dots, m\}$ represent the set of weights assigned to each criterion i based on which bridges will be prioritized for the installation of an anti-icing system. Also, let x_{ij} represent a numerical value of the i -th criterion for the j -th bridge. Then the worth or utility U_j of the j -th bridge can be calculated by a simple weighted average scheme:

$$U_j = \sum_{i=1}^m \alpha_i x_{ij} \quad (5.5)$$

Note that the criteria may correspond to various quantitative or qualitative properties with different units. For example, they can characterize the bridges' physical properties (e.g., length, width, surface type, age), the surrounding area (e.g., roadway alignment, body of water under the bridge), traffic conditions (e.g., ADT, truck percentage), weather conditions, accident frequency and severity, and the anticipated costs of an anti-icing system. Many of these qualitative and quantitative variables do not have units, or have different units. Also, they may differ significantly in magnitude. Therefore, the r_{ij} values are generally normalized to the 0–1 interval:

$$\|x_{ij}\| = \frac{x_{ij} - x_i^*}{x_i^{**} - x_i^*} \quad (5.6)$$

where:

$\|x_{ij}\|$ = normalized value of x_{ij} ,

x_i^* = worst possible value of the i -th criterion x_i , and

x_i^{**} = best possible value of the i -th criterion x_i .

Then, Equation 5.5 becomes:

$$U_j = \sum_{i=1}^m \alpha_i \|x_{ij}\| \quad (5.7)$$

Since the weights $0 \leq \alpha_i \leq 1$ and $\sum_{i=1}^m \alpha_i = 1$ for all i , and the normalized values $0 \leq \|x_{ij}\| \leq 1$, the calculated utility index will be in the interval $0 \leq U_j \leq 1$. If an optimum solution is sought (i.e., the bridge where the installation of the anti-icing system is the most desirable), the decision rule is to select the bridge with the greatest utility index:

$$U_{OPT} = \max_{\forall j} (U_j) \quad (5.8)$$

A prioritization of the bridge deck anti-icing system installations can be obtained by ranking all bridges based on their utility index in descending order.

5.4 COMPOSITE PROGRAMMING

Another technique for solving multiple-criterion decision-making problems with discrete decision variables is composite programming (CP) (Bardossy et al., 1995; Goicoechea et al., 1992). According to Szidarovszky et al. (1986), CP is a distance-based technique where each alternate feasible solution is evaluated based on its distance from an ideal solution. The ideal solution is the one that would perfectly satisfy all criteria (i.e., maximize all objectives). For example, in the case of the bridge deck anti-icing system installation prioritization problem, the ideal solution would represent a bridge where the system installation would be most desirable according to all criteria (e.g., accident records, ADT, bridge length, etc.), and the total cost (i.e., the sum of installation, operation, and maintenance costs) would be minimum. However, an ideal solution usually does not exist because of the existence of conflicting objectives. For example, installation of an anti-icing system may be more desirable on a longer bridge, but the installation, operation, and maintenance costs for such a bridge would also be higher compared to a shorter bridge. Therefore, alternative solutions can only be evaluated and ranked based on their distance from an imaginary ideal solution.

CP is capable of ranking a set of discrete alternatives (i.e., bridges where the anti-icing systems are to be installed) through a multi-level trade-off analysis. The logic of the CP-scheme is shown in Figure 5.1. Level 0 includes the same set of criteria that were used for calculation of the utility index. In CP, the normalized values for these criteria are called basic indicators. A normalized basic indicator scales down the difference between the actual and ideal value of a criteria to the 0–1 interval:

$$\|x_i\| = \frac{x_i^{**} - x_i}{x_i^{**} - x_i^*} \quad (5.9)$$

where:

x_{ik} = actual value of the i -th criterion,

$\|x_i\|$ = normalized value of x_i ,

x_i^* = worst possible value of the i -th criterion, and

x_i^{**} = best possible value of the i -th criterion.

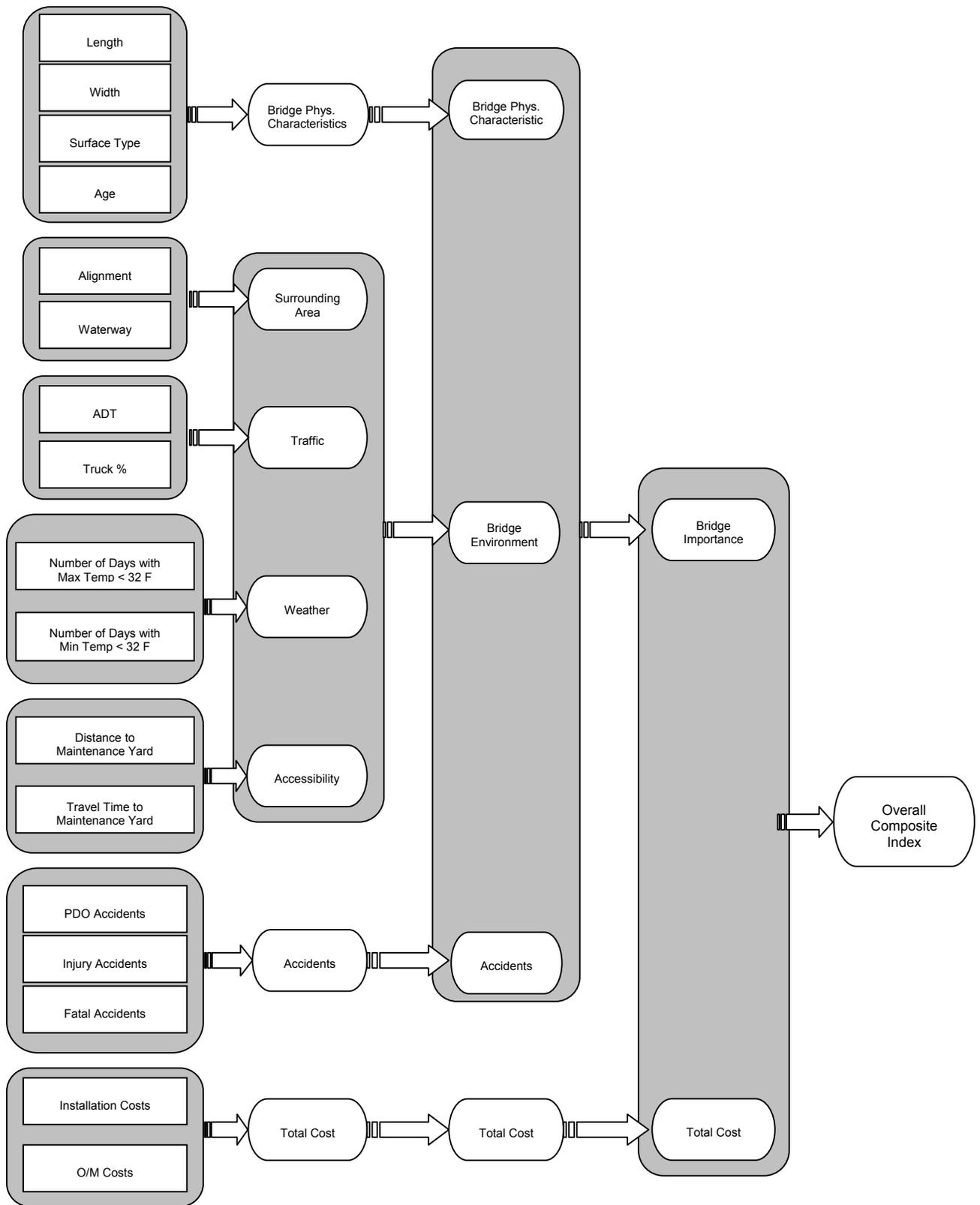


Figure 5.1 CP Structure for Prioritizing Bridge Deck Anti-Icing System Installations

Basic indicators expressing similar characteristics are clustered into groups. The 17 basic indicators in Level 0 are combined into seven groups. Then a composite index Φ_k is calculated for each group k by applying an L_p -norm to express the aggregate effect of the components of the groups:

$$\Phi_k = \left[\sum_{i=1}^{I_k} \alpha_{ki} \|x_{ik}\|^{p_k} \right]^{\frac{1}{p_k}} \quad (5.10)$$

where:

- Φ_k = composite distance for group k ,
- I_k = number of criteria in group k ,
- α_{ki} = weight associated with criterion i in group k ,
- $\|x_{ik}\|$ = normalized value of criterion i in group k , and
- p_k = a compromise programming parameter (balancing factor).

The L_p -norm in Equation 5.10 uses a double weighting scheme. The relative importance of the basic indicators within each group is expressed by the weights α_{ki} . On the other hand, the CP parameter p_k , also called as balancing factor, reflects the decision maker's concern with respect to the deviation from the ideal value. Greater p is associated with greater concern regarding the deviations from the ideal value. Note that the ideal value is 1 for each indicator variable (i.e., normalized value of a criterion), if the normalization by Equation 5.10 is used.

The composite indices Φ_k calculated in Equation 5.10 aggregate the effect of the basic indicators in Level 0 into a reduced number of composite indicators (i.e., decision variables) in Level 1. The composite indicators in Level 1 can be further clustered into meaningful groups, and new weights α_{ki} and balancing factors p_k assigned to new composite indicators and groups. The number of groups, and the number of decision variables in the groups are smaller than those in Level 0. Using Equation 5.10, a new composite distance can be calculated within each group of Level 1. The process continues through successively higher levels, as shown in Figure 5.1, until an overall composite distance is calculated. This overall composite distance measures the deviation of a feasible solution (i.e., bridge installation alternative) from the ideal solution, and can be used to prioritize the installation of the anti-icing system installation. The smaller this composite distance for a bridge, the higher it is ranked on the priority list for system installation.

COMPARISON OF ALTERNATIVE DECISION-AID FORMATS

The decision-aid formats were compared by applying them to a sample set of 26 bridges in Nebraska. Results of prioritization of these bridges using the four methods are shown in Table 6.1. Bridges are listed here in the order ranked by the NDOR based on the number of accidents occurring during icy and snowy conditions.

It is evident from Table 6.1 that the rankings by the four methods are different from NDOR's preference list, which was based on accident frequency under icy and snowy conditions only. For example, the bridge ranked at the top by NDOR was ranked 10th by benefit-cost and cost-effectiveness analyses, and 21st by utility index and CP methods. The reason for the differences is the additional selection criteria used by the four methods. In addition to accident frequency, the benefit-cost and cost-effectiveness analyses incorporate system costs and accident severity in the selection process. Utility index and CP expand the selection criteria and incorporate the decision maker's preferences. Therefore, it is reasonable that the prioritized lists generated by the four methods will be different than the NDOR's list. Additionally, the fact that NDOR's ranking was based on 1995–1999 accident data while the four methods utilized 1988–2000 data also may have contributed to some of the differences.

Rankings generated by the benefit-cost and cost-effectiveness analysis are identical. This is true because the weights of the five levels of injury severity used in the calculation of SII were proportional to the unit costs of these injury types. A different set of weights would have resulted in different ranking. Results obtained from the utility index and CP methods show significant differences with respect to those of the benefit-cost and cost-effectiveness analyses, and especially with respect to NDOR's rankings. It is important to note that rankings on the basis of both the utility index and CP are very sensitive to the relative weights among selection criteria. Therefore, the results in Table 6.1 correspond to a specific set of weights, which were selected simply for the purpose of demonstrating the methods. Other weights may result in quite different rankings. The purpose of the weights is to incorporate the decision maker's preferences and concerns with regard to the criteria. Table 6.2 presents the weights assigned to each criterion used in calculating the utility index in this analysis. Criteria not listed in the Table 6.2 were assigned zero weights.

Table 6.1 Prioritized List of Anti-icing System Installations for Sample Bridges

Bridge ID	Rank				
	NDOR	B/C Analysis	C/E Analysis	Utility Index	CP
S080 31446	1	10	10	21	21
S080 18181	2	2	2	1	1
S080 44207	3	13	13	19	7
S080 21627	4	3	3	2	2
S080 20100	5	5	5	5	5
S080 29139	6	6	6	6	6
S080 40797	7	4	4	4	4
S080 21088	8	16	16	14	14
S080 40977	9	15	15	12	9
S034 22521	10	20	20	22	22
S034 33251	11	23	23	13	15
S080 10119	12	24	24	16	20
S080 40375	13	8	8	15	16
S080 18470	14	12	12	20	17
S080 39165	15	9	9	11	10
S080 43922	16	11	11	10	12
S080 40414	17	7	7	7	8
S080 42729	18	17	17	26	26
S077 11185	19	25	25	25	25
S275 15424	20	1	1	3	3
S080 40429	21	14	14	9	13
S080 32815	22	18	18	8	11
S370 01566	23	21	21	18	18
S081 04546	24	22	22	17	19
S044 04856	25	26	26	23	23
S077 18870	26	19	19	24	24

Table 6.2 Weights Used for Utility Index Calculations

Criteria	Weight (")
Length of bridge span	0.02
ADT	0.02
Days with Maximum temp < 32° F	0.01
Days with Minimum temp < 32° F	0.03
Travel time to maintenance yard	0.02
Fatality	0.43
Injury	0.08
PDO	0.02
Installation cost	0.21
Operation cost	0.08
Maintenance cost	0.08

In the case of the CP method, an additional parameter, the balancing factor p must also be defined. As stated earlier, p reflects the decision maker's concern regarding deviation of the actual value of a criterion from its ideal value. Table 6.3 provides the weights and balancing factors for each of the basic indicators and groups used in this analysis. As with the utility index, these weights are simply selected for demonstrating the methodology. These weights would need to be based on the NDOR's preferences and knowledge of the bridge locations and experience with anti-icing systems in Nebraska in order to provide a meaningful prioritization.

A comparison of the decision-aid formats is presented in Table 6.4. A major difference among the four methods is that the benefit-cost and cost-effectiveness analyses are single-criterion optimizations, whereas the methods of utility index and CP are multi-objective optimizations. The first two methods maximize the benefit and safety improvement per unit cost, while the latter two seek the best possible compromise solution among several, often conflicting, objectives. It should be noted that both utility index and CP can also be applied as single-criterion optimization methods by assigning unit weight to one of the criteria and zero weight to the rest.

Table 6.3 Weights and Balancing Factors Used in CP Calculations

Level 0			Level 1			Level 2			Level 3		
Basic Indicators	"	p	Group	"	p	Group	"	p	Group	"	p
Length of Bridge	0.67	1	Bridge Physical Characteristics	1.00	1	Bridge Physical Characteristics	0.15	1	Bridge Safety and Importance	0.67	1
Approach Roadway Width	0.33										
Surface Type	0.00										
Age	0.00										
Alignment	0.33										
Waterway	0.67										
ADT	0.67	Traffic	0.36								
Truck %	0.33										
Days with Max. Temp < 32	0.25	1	Weather	0.36	1	Bridge Environment	0.08				
Days with Min. Temp < 32	0.75										
Distance to Maintenance Yard	0.00	1	Accessibility	0.14							
Travel Time to Maintenance Yard	1.00										
Fatality	0.80	1	Accidents	1.00	1	Accidents	0.77				
Injury	0.16										
PDO	0.04										
Installation Cost	0.56	1	Total Cost	1.00	1	Total Cost	1.00	1	Total Cost	0.33	
Operation Cost	0.22										
Maintenance Cost	0.22										

" = weight, p= balancing factor.

Table 6.4 Comparison of Alternative Decision-Aid Formats

Properties	B/C Analysis	C/E Analysis	Utility Index	CP
Single-criteria optimization	X	X	(X)	(X)
Multi-objective analysis			X	X
Conflicting objectives permitted			X	X
Expandable set of criteria			X	X
Decision maker's preference incorporated			X	X
Dual weighting scheme				X
Multi-level analysis				X
Structural flexibility				X

The set of criteria used by the utility index and CP methods are easily expandable; their number is limitless. Another important advantage of these two is that the decision maker's knowledge and expertise can be incorporated in the selection process. Decision maker's preferences among specific criteria can be incorporated by assigning appropriate relative weights. CP goes even further by using a double weighting scheme, which makes it possible to incorporate the decision maker's concern regarding the deviation of actual value of a criterion from its ideal value. The multi-level structure of CP enables ranking based on either an overall composite index, which aggregates the effect of all criteria, or an internal composite index calculated for any group at any level. For example, it is possible to rank bridges on the basis of bridge physical characteristics, weather conditions, or traffic conditions within the same trade-off analysis. The structure of the CP approach is flexible in the sense that grouping of basic indicators, and composite indexes are completely user-defined at each analysis level.

PHASE I CONCLUSIONS

In Phase I of this research project, factors relevant to prioritizing installation of bridge deck anti-icing systems were identified and a database quantifying these factors was created in a GIS environment. To prioritize bridges for system installation, a decision-making module was developed in a spreadsheet environment. This decision-making module incorporates several criteria important in the prioritization of bridge deck anti-icing system installations. In addition, it is capable of prioritizing these installations in four decision-aid formats: benefit-cost, cost-effectiveness, utility index, and CP. These four formats were applied to a set of 26 bridges proposed by NDOR as potential locations for installation of anti-icing systems.

Prioritization results from all four formats differed from those supplied by the NDOR, which was based on accident frequencies under icy and snowy conditions only. The differences are explained by the additional selection criteria included in the four formats and the fact that NDOR's list was based on 1995–1999 accident data whereas the four formats utilized 1989–2000 data.

A major difference among the four formats is that the benefit-cost and cost-effectiveness analyses are single-criterion optimizations, whereas the utility index and CP are multi-objective analyses. The first two formats maximize the benefits and safety improvement per unit cost associated with the installation of anti-icing systems. The utility index and CP formats seek the best possible compromise solution among several conflicting objectives.

Based on its extensive capabilities and adaptability, the CP format appears to best suit the needs of prioritizing locations for the installation of automatic bridge deck anti-icing systems. However, it is important to note that rankings based on the CP format are sensitive to the relative weights among selection criteria. Therefore, this method should only be used when the user feels confident about the weights assigned to the selection criteria. If the user is not comfortable assigning weights to the selection criteria, the benefit-cost format is preferable.

Chapter 8

PHASE II WORK PLAN

Research during Phase I of this project has identified several aspects of the prioritization of bridge deck anti-icing system installations that merit further investigation. The results of this effort would greatly enhance the applicability, validity and implementation of the decision-making process developed in Phase I. The proposed work plan for Phase II of this research would include the following primary tasks.

TASK 1 – VERIFICATION OF WEIGHTS

The decision-making process relies heavily on the weights assigned to the selection criteria (accidents, injuries, bridge length, etc.), which ultimately determines the priorities of bridge deck anti-icing system installation. However, current literature or other sources do not offer help on determining appropriate weights for the various factors considered during Phase I. These weights must be based on the preferences of NDOR. Therefore, a survey of NDOR district engineers, maintenance supervisors, and other appropriate NDOR personnel would be conducted. This survey would solicit input on the relative importance of the various criteria considered in Phase I. The survey results would be compiled to assign appropriate weights to each of the criterion used in the decision-making module.

TASK 2 – ANALYSIS OF EXISTING FACILITIES IN NEBRASKA

A few bridges in Nebraska have recently been equipped with automatic anti-icing systems. The performance of these bridges would provide useful Nebraska-specific data that could be used to refine the decision-making process. For example, accident history for these locations could be evaluated to determine how it has been affected by the installation of the anti-icing system. Similarly, maintenance and operation costs could be refined by considering information from these systems. Reliability of the existing systems could also be investigated and incorporated into the analysis and decision-making process.

TASK 3 – GIS INTERFACE

The decision-making module in MS Excel currently lacks a GIS interface, which would enable it to utilize the excellent presentation capabilities of GIS. Currently, users of the decision-making module cannot efficiently view or run queries on their analysis results. During Phase II, the decision-making module developed in MS Excel would be coupled with ArcView GIS software, so that users could view and query the results of their analysis. Users would be provided with a powerful, yet user-friendly computer interface which could be used for both data input and viewing the results of their analysis and running additional queries based on the initial results. This would significantly enhance the usefulness of the decision-making module.

TASK 4 – USER GUIDE AND TRAINING

An easy-to-follow user guide would be developed for NDOR personnel that would illustrate the use of the decision-making module. It would also include information on the operation of the module, running multiple queries on the database, and obtaining high-quality graphical output from the GIS interface. A training session would be arranged at a mutually convenient time in which the research team would demonstrate the use and functionality of the system.

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