NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 182

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TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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TRANSPORTATION RESEARCH BOARD
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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FOREWORD

By Staff
Transportation
Research Board

This report will be of interest and usefulness to highway maintenance engineers and others involved in selection of countermeasures for control of localized ice and frost on bridge decks. A cost-benefit methodology involving mathematical models that can be used to compare the cost of a countermeasure under consideration for reducing the accident problem with the monetary savings to be gained through application of the countermeasure is reported. A mathematical model for predicting the annual number of ice and snow accidents on a bridge, given various characteristics of the bridge site, is also described. Testing of the methodology with the limited amount of usable data that could be found in the literature and through contact with state highway and transportation departments gave encouraging results.

Ice and frost on localized spots of otherwise clear traveled ways are universally recognized as creating a particularly hazardous condition for unsuspecting or inattentive drivers. The formation of ice and frost on bridge decks while the rest of the traveled way remains ice- and frost-free is a well known phenomenon. Data available to the project led to a rough estimate that 25,000 accidents costing $80 million occur annually due to ice and frost on bridge decks in the United States. Numerous countermeasures have been used, and others have been considered and sometimes researched. However, attempts to justify their additional costs on a rational basis have not met with much success. As a consequence, development work has been hampered, countermeasures have been tried and then abandoned in the belief that they were too costly, and others may not be getting the attention they deserve because of lack of information regarding their cost-benefit relationships.

This project has produced a means of cost-benefit analysis for estimating cost savings that can accrue through accident reduction by application of special ice- and frost-control systems for bridge decks. It requires a knowledge of the frequency of various roadway surface conditions, accident rates and costs, and costs that can be charged to the countermeasure. The use of a limited amount of available data in the models that were developed for the assessment methodology produced reasonable results. These data, however, are not for universal application. Each user of the methodology needs to develop a data base for his own area of interest. This data base can be generated using procedures developed in the study.

Most potential users will find that not all of the data needed for application of the methodology, although collectable, are readily available in presently maintained record systems. Among the missing information are sufficiently precise data regarding the frequency and extent of local bridge deck icing and frosting requiring application of a countermeasure, and sufficiently precise accident data for icy and frosty conditions.

CONTENTS

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The research reported herein was performed under NCHRP Project 6-11 by the Midwest Research Institute.

The work was carried out in the Engineering Sciences Division, under the administrative direction of Drs. F. V. Morriss, Michael C. Noland, and William D. Glauz. Robert R. Blackburn was the principal investigator. Other responsibilities were as follows: Donald Kobett (countermeasures, data collection and cost estimates); Andrew D. St. John (formulation of benefit and cost models); John C. Glennon (simplification and parametric analysis of benefit and cost models); Michael C. Sharp (bridge classification model, road surface exposure determination and statistical analysis); and Rosemary Moran (computations).

Many state highway officials lent their assistance in assembling data and information for the program. Special acknowledgment and appreciation are due for assistance given by key members of the highway or transportation department staffs of Arkansas, California, Illinois, Iowa, Kansas, Michigan, Missouri, Ohio, Pennsylvania, Texas, and Virginia.

Appreciation is also due the state highway police of Iowa, Kansas, Missouri, Texas, and Virginia, who assisted the research effort by collecting special bridge accident data.

Finally, useful information and suggestions provided by Professor C. Birnie, Jr., Pennsylvania State University; Dr. Robert Olson, Texas Transportation Institute; and others are gratefully acknowledged.

ECONOMIC EVALUATION OF ICE AND FROST ON BRIDGE DECKS

SUMMARY

The objective of this research was to develop a comprehensive cost-benefit methodology, complete with a set of realistic parameter values, that can be used by a highway administrator to determine the added design or extra maintenance cost justified to prevent or remedy ice or frost on bridge decks. The emphasis, throughout, was on localized icing—that is, situations where the bridge deck and approach pavement conditions are dissimilar.

The activities included a literature search, a survey of selected state highway departments, the formulation of a cost-benefit methodology, an analysis of model parameters, the collection of cost data on preventive and remedial techniques in current use, and the collection of a sampling of data on bridge accidents and frequency and duration of localized bridge icing. The research also comprised the development of a subsidiary net cost model, the formulation and evaluation of a bridge classification model, and the computation of illustrative examples of the cost-benefit methodology application.

The critical literature review of research related to the program objectives, supplemented by correspondence and personal visits with several state and local highway engineers, pointed out several basic needs. Information pertaining to the incidence of localized frosting or icing of bridge decks, and accidents occurring under such conditions, was determined to be virtually nonexistent. This prompted a collection of the lacking localized bridge icing data and bridge accident data on a sampling basis. These data in combination with other estimates indicate that there may be on the order of 25,000 such accidents yearly, reflecting a cost to society of about $80 million. These figures are probably within 50 percent of the true values.

The cost-benefit methodology consisted of two models: a benefit model and a cost model. The benefit model is to be used to calculate a yearly dollar benefit defined as the difference between accident costs without a special localized icing countermeasure and accident costs with the countermeasure. It requires knowledge of the frequency of various roadway surface conditions, accident rates, and accident costs. The cost model includes those annual costs directly or indirectly incurred by a countermeasure system to combat localized ice or frost, including detection/prediction devices, the countermeasure per se, and repair and maintenance costs incurred later because of the countermeasure. In all cases the costs charged include only the costs that are above and beyond those occurring without the special localized icing countermeasure system.

The cost model is then combined with the benefit model to determine the benefit/cost ratio for a specific countermeasure system.

A special model was developed to describe the net costs to a state of a countermeasure system, by including the portion of the costs of accidents borne by the state. This model used legal defense and liability costs as an illustration.

A technique was developed for predicting the annual number of ice and snow accidents on a bridge, given various characteristics of the bridge. The method utilizes bridge accident probabilities based on average daily traffic, length, width, location (urban/rural), type of crossing (water/other), highway type (divided/undivided), and bridge type (concrete/other). Application of the model to bridges in Ohio showed that it was less desirable for a bridge to have the following individual characteristics: rural, not over water, divided, and not constructed of concrete. Moreover, accident involvement increases with ADT and length; the width effect was not clear-cut.

Numerical examples of the cost-benefit analysis were calculated using data from selected regions to: (1) demonstrate the application of the methodology, considering a variety of countermeasures; and (2) assist in refining the parameter determination. The benefit/cost ratio (B/C) for the cases considered ranged from a low of 0.18 to a high of 2.27. Half of the B/C values obtained for countermeasures that were applied to individual, selected bridges exceeded unity. However, all of the B/C values associated with countermeasures appropriate to areawide groupings of bridges were less than unity. The occurrence of low values was rationalized in that areawide winter maintenance practices can not be justified solely by accident reductions.

It was concluded that the cost-benefit methodology developed is comprehensive in scope and has the flexibility to represent a variety of situations and countermeasure systems. The application of the methodology to sample cases illustrated geographical variations. A technique is presented to estimate the exposure times to various road surface conditions. Each highway engineer wishing to apply the methodology and bridge model needs to develop for the area of interest a more precise accident data base with regard to location (bridges) and road surface conditions (frost, localized ice, etc.). This data base can be generated using the data collection procedures described in this study.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

Significant national and international interest has grown on the problems of detecting, preventing, or removing ice, snow, or frost on bridge decks. This interest is demonstrated by the investigations described in a Highway Research Board publication on "Snow Removal and Ice Control Research" (*1*). Research is currently active on ice detection or prediction devices, the development of noncorrosive deicers, the evaluation of bridge deck deterioration, and techniques of bridge or pavement heating.

The amount of active research implies that localized ice or frost on bridge decks (while the approach pavements remain ice- or frost-free) is accepted as a serious problem in many states. Indeed, most highway engineers agree that an isolated icy section of roadway is an obvious safety hazard to the unknowing motorists. But, the degree and pendix C) with a cost of about $80 million (based on an average cost of $3,180/accident; see Appendix D). The annual U.S. maintenance costs for the treatment or prevention of localized bridge icing are equally difficult to assess. In 1967, one researcher estimated an annual outlay of $150 million for snow removal in snow belt states (*2*). If only 1 percent of this amount is spent on bridges, the annual maintenance cost for icy bridges is $1.5 million. extent of this hazard are unknown. That is, for accident-reduction efforts, few hard data are available to justify the appropriate level of localized countermeasures. Consequently, highway departments in their maintenance practices often assume that the problem is significant.

Precise estimates of the annual number of accidents for localized bridge icing conditions are almost nonexistent. From data available, however, a rough estimate places the annual number at 25,000 accidents nationwide (see Ap-

This estimate, however, may be low because it ignores the damage done to bridge decks by deicing chemicals.

The legal liabilities of a state toward prevention or removal of ice on bridges also have received considerable attention. More and more, a state's maintenance policy is influenced by potential legal consequences. Many times, the courts have ruled "icy bridge" warning signs as insufficient; ice removal or prevention is also necessary. Therefore, some states have even decided not to use icy bridge warning signs because of the potential legal problems.

The fact that bridge decks become coated with frost, ice, or snow sooner and more often than the approach pavement is well known, even by the courts, and the mechanisms are well understood. Also, the extent of localized icing varies widely not only between states but also between locations and between bridges. These variations are related to the microclimate associated with an individual bridge, as well as to other local roadway and traffic factors. These factors, in combination with an icy pavement condition, can contribute to accident frequency. The bridge itself has added importance because it presents the driver with special hazards, such as bridge abutments, narrower roadways, and the lack of an escape route. Because of the localized nature of the problem, a meaningful universal statement about the cost-benefit of icy bridge maintenance has not been possible.

What the state highway administrator needs, therefore, is a methodology to evaluate the potential accident reduction benefits for the winter conditions specific to his state's environment. These benefits must be balanced against the added design or increased maintenance costs of preventing or removing ice and frost on bridge decks.

A program designed to develop this methodology, "Economic Evaluation of the Effects of Ice and Frost on Bridge Decks," was conducted by Midwest Research Institute under NCHRP Project 6-11 and is reported here. Specifically, the program objective was to develop a methodology, including cost-benefit or cost-effectiveness procedures, complete with a set of realistic parameter values, so that a highway administrator can determine the added design or maintenance costs justified to prevent or remove ice and frost on bridge decks.

RESEARCH APPROACH

The program objective was met through a multiphase research approach. This approach is outlined, as follows, together with a brief description of the activities of each phase.

Research Review

Past and current research pertinent to the program objective was critically reviewed to identify and quantify the parameters required by the methodology. The major sources of published information were the Highway Research Board publications, the Highway Research Information Service (HRIS), the National Highway Traffic Safety Administration's (NHTSA) documentation center, and the National Safety Council.

Computerized literature searches were obtained through HRIS on the following subjects:

- Accidents from slick bridge decks and pavements.
- Human response to warnings by motorists.
- Automatic devices to warn of bridge deck icing and deicing implementation.
- Prevention of concrete bridge deck deterioration.
- Study of frost or ice forming on bridge decks.

A search was also performed through NHTSA on the first three subject categories. Also, an awareness of current publications was maintained by monitoring appropriate abstract journals, notably:

- *U.S. Government Research and Development Reports.*
- *Highway Research Abstracts.*
- *Highway Safety Literature.*

Many publications were reviewed as a result of these searches. They were examined for data on localized frosting and icing of bridge decks in the areas of:

- Frequency and extent of occurrence.
- Accident statistics.
- Countermeasures.
- Special maintenance policies.
- Countermeasure and maintenance costs.
- Characteristics of bridges with high frequency of occurrence.
- Effect of deicing chemicals on bridge deck deterioration.

These sources of data were supplemented through correspondence and personal visits with other researchers both in the United States and elsewhere, and with several state and local highway engineers.

It was determined, from the literature examined and states visited, that data on localized frosting or icing of bridge decks are almost nonexistent. The reason for this lack of data is that the localized condition is not specifically identified, but instead is inextricably included within the general categories of ice and snow. For example, accident occurrences under localized icing conditions can not be separated from accident statistics or from most accident records. Similarly, maintenance procedures are not detailed to the point of requiring specific records on the treatment of localized icing conditions.

Some information is available on the effect of deicing chemicals on bridge deck deterioration. Experimental studies have been and are being conducted by several investigators.

Discussions of the pertinent literature are presented and referenced in the various sections of this report. Background information and data obtained from the various states are discussed separately in Chapter Two under "Summary of Personal Visits to Various States" and in Appendix A.

Cost-Benefit Methodology Formulation

The cost-benefit methodology is divided into two models; a benefit model and a cost model. The benefit model is used to calculate an annual dollar value of accident reduction benefits provided by a particular countermeasure system. Annual benefit is defined as the difference between

accident costs per year without a special localized icing countermeasure system and accident costs per year with the countermeasure system.

The cost model includes those costs directly or indirectly incurred by a countermeasure system to combat localized ice or frost. In all cases, charged costs include only those that are above and beyond costs occurring without the localized icing system and countermeasure. The cost model is then combined with the benefit model to calculate the benefit/cost ratio for a specific countermeasure system.

Also of possible interest is the net cost to a state of a countermeasure system, including those costs of accidents borne by the state. Therefore, a special model was also developed to describe the legal defense and liability costs.

Further details of the cost-benefit methodology are discussed in Chapter Two under "Cost-Benefit Methodology" and in Appendixes B and F.

Model Parameter Determination

This phase entailed the identification of the numerical values of the model parameters and the development of methods for determining others. A current estimate of accident costs by severity was obtained from the literature. Accident rates, both with and without the presence of localized ice or snow, were computed for selected areas of the country using accident and weather records. Maintenance records, engineering judgment, and direct on-site observations of bridges during hazardous conditions were used in estimating various road surface exposure times, including localized icing conditions.

This phase also involved a thorough investigation of various techniques for and the costs of preventing or removing localized ice and frost from bridge decks. The examination of the countermeasures for localized hazardous bridge decks and those for uniformly hazardous roadways helped the development of a general cost model. Data on countermeasures were assembled from the published literature and from maintenance and cost accounting divisions of several state highway departments.

Quantitative descriptions of the data collected for the models are discussed in Appendixes C, D, and G.

Bridge Classification Model Formulation and Testing

Application of a cost-benefit analysis to an arbitrarily selected set of bridges may yield discouraging results. On the other hand, application to bridges with known high accident rates for localized ice or frost conditions, or to bridges with certain common characteristics, may yield substantially different results. Because the frequency of accidents on ice on most bridges is relatively low, however, a technique is needed to pinpoint those bridges where detection systems and/or special maintenance would give the greatest benefit.

A method was developed for classifying bridges using locational, geometric, and traffic data readily available to the highway engineer. The method ranks bridges based on predicted accident experience for ice or snow conditions. The model is briefly discussed in Chapter Two under "Bridge Classification Model" and in more detail in Appendix I; an example of its application using a sample of Ohio bridge accidents is presented in Chapter Three under "Application of Bridge Classification Model."

Application of the Cost-Benefit Methodology to Selected Sample Cases

Numerical examples of the cost-benefit analysis are presented in Appendix H to illustrate the application of the methodology and to assist in refining the parameter determination. The models were applied to bridges in certain regions of Iowa, Ohio, and Texas; and to a specific bridge in Virginia, considering a variety of countermeasures. The examples reflect a sample of geographical climatic conditions throughout the United States. The details of the numerical computations are discussed in Appendix H, with the results presented in Chapter Three under "Application of Cost-Benefit Methodology to Selected Cases."

CHAPTER TWO

FINDINGS

SUMMARY OF PERSONAL VISITS TO VARIOUS STATES

The research team visited nine state highway departments for several purposes. First, the team desired to determine the availability of certain data needed for the development of the cost, benefit, and bridge classification models. The kinds of data sought involved highway maintenance practices and costs associated with the treatment of localized ice and frost on bridge decks. Also of interest were bridge accident data (or rates) for all kinds of pavement conditions, including localized ice and frost. Second, the team wished to acquaint as many maintenance personnel as possible with the objectives of the program before winter. By doing so, it was hoped that individual state maintenance departments would assist in collecting some meaningful data during the winter on localized icing conditions.

The states visited were Arkansas, California, Iowa, Kansas, Michigan, Missouri, Ohio, Pennsylvania, and Virginia. These states were selected to represent a sampling of the availability of needed data throughout the United States. The significant findings common to the states visited are presented first, followed by a summary of the availability of specific kinds of data. A brief description of the results of each of the individual visits is given in Appendix A.

General Findings

1. Maintenance costs for the treatment of localized ice and frost are difficult to isolate in existing state records. The costs of winter maintenance are usually lumped into a general category of snow and ice control.

2. The increased costs of bridge maintenance due to deicing chemicals are difficult to ascertain from state records. In several states, the repair or replacement costs of a deteriorated bridge deck are combined with other gross maintenance costs. In addition, the states do not generally agree about the effects of deicing chemicals on bridge deck deterioration.

3. The states do not routinely keep records on the frequency of localized ice and frost or on the susceptibility of a particular kind of bridge to localized icing. Experienced maintenance personnel (particularly foremen with many years of experience in a particular area) do have a "feel" for the bridges that ice up before others. Conceivably, some clues on localized icing conditions can be obtained from these experienced maintenance foremen. Information on icing conditions may also be contained in maintenance foreman diaries where diaries are required.

4. Extreme care must be exercised in assembling and analyzing bridge accident data. Sometimes, an accident is classified as a bridge accident if any part of the bridge is struck. Many accidents precipitated by the bridge pavement condition are probably recorded as nonbridge accidents. This kind of record is possible, particularly when the collision occurs on the exit end of the bridge (some accidents attributed to bridges could have resulted from approach design or other causes upstream of the bridge). This shortcoming in the accident data results primarily from a lack of uniform definition of a bridge accident.

5. None of the accident-reporting forms used by the states visited was specific enough to note the occurrence of bridge accidents under *localized* ice and frost conditions. The bridge accident data available from the states were for general wet, dry, snowy, or icy pavement conditions. The Michigan accident data were an exception: a category of "frosty" bridges was included. These data, however, are extracted by data encoders from remarks noted by the investigating patrol officer. Another exception was the California accident report form, which has a category of frost *or* ice.

Specific Findings

A summary of the data available from the states is given in Table 1. The table presents sources of bridge frosting data, maintenance cost details, and the completeness or validity of the computerized bridge accident data.

The diary kept by a maintenance foreman is a potential source of information on the occurrence and treatment of localized icy and frosty bridge decks. Because a diary is kept, however, does not guarantee that it contains useful or consistent data on localized icing; in many states, these data are not required routinely. This fact, combined with the difficulty in reviewing the diaries (most are retained at the local maintenance garage locations), discouraged the use of existing maintenance diaries as a ready source of information on localized icing. Instead, an attempt was made to collect meaningful data on localized icing with a minimum effort in several maintenance areas of some of the states visited. The maintenance departments of Arkansas, Iowa, Michigan, and Pennsylvania agreed to record certain data associated with localized ice and frost bridge decks, during the 1970-1971 winter. California was not formally requested to record these data because that State had previously assembled a sample of the data for its own needs (see Appendix A).

Sample data forms and recording procedures were developed to ensure consistent reporting among the four states (Arkansas, Iowa, Michigan, and Pennsylvania). The data to be recorded were those associated with the occurrence and treatment of ice, frost, and snow-packed conditions for those bridges in the sample maintenance areas. The dates and times that the bridges became hazardous were requested along with estimates of the times required for the pavement to become dry after treatment. The countermeasures used by the maintenance crews in treating ice and snow-packed combinations (such as sanding, salting, plowing, etc.) were also to be noted, along with certain meteorological factors, including sky conditions, kind of precipitation, and temperature conditions at the beginning and end of precipitation.

The data collected by the states on the occurrence of frost and estimated durations that various pavement conditions existed (dry, wet, locally icy, and generally icy) were expected to help identify the numerical values for roadway exposure times that appear in the benefit model. Unfortunately, the data received were incomplete for some areas, and in other cases the data forms were misinterpreted. Although some useful information was obtained as a result of the data request, it would have been too costly to extract the meaningful data.

Some meaningful maintenance data, however, were obtained from one of the Iowa maintenance areas. These data, collected on an experimental study of ice and snow detection systems (*3*), were useful in estimating road surface conditions (see Appendix E). Personal contacts with the maintenance foreman supplying the particular Iowa data undoubtedly accounted for its usefulness. Personal contacts with the other maintenance personnel supplying data were not possible.

Maintenance data recorded during the 1970-1971 winter were not sufficiently complete to specify reliably the extent or frequency of localized icing on bridge decks. Special winter maintenance data on localized icing were again collected during the 1972-1973 winter. The states participating in this second effort were Illinois, Iowa, Michigan, Ohio, Texas, and Virginia. Personal visits were made to each of these states to discuss specifically the data collection with the local maintenance foremen selected. Improved data recording forms were developed and distributed during the visits. The data assembled from the second effort were extremely useful and are described in Appendix C.

Bridge accident data were obtained from several of the state highway departments visited (see Table 1). (Bridge accident data were also obtained from other sources mentioned in Appendix C.) The bridge accident data received included experience for specific bridges (Arkansas, Michi-

TABLE 1

SUMMARY OF DATA AVAILABLE FROM STATES VISITED

States Visited	Data Requested or Obtained on Frost Occurrence	Maintenance Foreman Diary		Maintenance Cost Breakdown		Computerized Bridge Accident Data**	Pavement Conditions Coded (in Addition to Wet and Dry)				States from Which Obtained Bridge Accident Data
		Required	Not Required but Kept in Some Areas	In Addition to Total Cost of Snow and Ice Control*	Finest Geographical Level		Frost	Ice	Snow	Ice and Snow Combined	
Arkansas	X			a	Route and Section	2				X	X
California	X		X	c	Route in County	2	Frost or ice		X		X
Iowa	X		X	b	State	1		X	X		X
Kansas				c	Sub-District	2				X	
Michigan	X	X		b	County	2	X	X			X
Missouri			X	c	District	2		X	X		
Ohio				None	County by Roadway Type	1				X	X
Pennsylvania	X	X		c	County	1		X	X		
Virginia				b	Route and Section	3		X	X		X

* a - Material and manpower costs combined.
b - Material costs alone.
c - Individual costs for material, manpower and equipment usage.

** 1 - Includes bridges directly and indirectly involved in the accidents.
2 - Includes bridges only directly involved in the accidents.
3 - Bridges are not specifically listed.

gan, and Virginia), for specific counties (California), and for entire states (Iowa, Michigan, and Ohio). The completeness and/or validity of the computerized bridge accident data available from the states vary considerably, as shown in Table 1. The bridge-accident data most applicable to this study included those crashes associated both directly and indirectly with bridges. The data that include only direct collisions with bridges omit those accidents where the bridge was not physically struck, but was a contributing factor.

Appendix C discusses the bridge-accident data collected and those selected for application of the models. The accident-rate data show that an hour of ice or snow is more hazardous than, say, an hour of dry pavement conditions. The degree of hazard depends on geographic location.

A subsidiary analysis was performed to see if a correlation exists between relative accident rates on ice or snow and exposure times to ice or snow conditions. The results, presented in Appendix C, indicate that driving on bridges with ice or snow is more hazardous in areas that are less exposed to ice or snow.

COST-BENEFIT METHODOLOGY

Introduction

A cost-benefit model is an economic tool commonly used to compare alternative strategies. The highway engineer often uses such tools for setting priorities in allocating funds to various highway safety projects. In this report, the application of a cost-benefit model is for comparing alternative winter maintenance strategies for localized ice and frost on bridge decks.

The application of a cost-benefit model results in a ratio of dollar benefits (B) to dollar costs (C), B/C. This ratio is calculated for each winter maintenance strategy (localized countermeasure system) considered. In this report, the benefit and the cost are calculated independently using a benefit model and a cost model. Then, other things being equal, the countermeasure system with the highest benefit-to-cost ratio is the most desirable for implementation.

This section first discusses the benefit model and then the cost model. In addition, a summary of the kinds of countermeasure systems is given. Finally, some cost aspects are examined that might be included in an evaluation of the total cost of a winter maintenance strategy to a state, which goes beyond those costs commonly considered within the highway department's budget.

The Benefit Model

The benefit model is used to calculate a dollar value of the annual accident reduction benefits provided by a countermeasure system. Annual benefits are defined as the difference between accident costs per year without special countermeasures and accident costs per year with the countermeasures.

First consider a grossly oversimplified model. Assume that, with no countermeasure, the bridge(s) is icy N_I hours a year, is dry N_D hours a year, and in this simple model only icy or dry conditions ever occur. (That is, $N_I + N_D =$ 8,760, the total hours per year.) Let a_I be the accident rate (accidents per hour) on icy bridges and a_D be the accident rate on dry bridges. Also, assume that accidents cost K dollars each.

Now envision a perfect countermeasure as one that eliminates *all* accidents on icy bridges. The yearly cost of these accidents is Ka_IN_I; this is also annual benefit for the perfect countermeasure. In reality, however, the accident rate for a countermeasure will not drop to zero, but will be reduced to the accident rate for dry bridges. That is, the accident rate, a_D, would yield a "loss" in benefit for the period N_I. The net yearly benefit then is:

$$B = Ka_I N_I - Ka_D N_I \qquad (1)$$

A more comprehensive model is desirable for two reasons: (1) it will identify needed input data, and (2) it will enable subjective or engineering judgments to be made in the interim in the context of a more complete overview of the system. To be comprehensive, such a model will necessarily include some rates that can not be evaluated with available data. The unquantified data should not serve as a deterrent at this point in the development, however.

The comprehensive model must have well-defined terms and the flexibility to represent a variety of conditions and countermeasure systems. Some of the requirements for definition and flexibility are discussed briefly to explain the model.

Normally, a benefit model compares a situation resulting from some particular application countermeasure with the situation in its natural state. In the localized icing problem, however, this approach is unrealistic and the resulting model is not possible to implement. No data exist on such parameters as accident rates and frequency of occurrence under conditions of *no countermeasures at all.* Therefore, some other basis is needed. In this study, the situation as it presently exists in a state with *generalized* icing countermeasures but with *no specialized* countermeasures for localized icing was chosen as the basis or comparative case. This way, a well-defined basis exists for obtaining relevant data. It has the disadvantage, however, of varying from state to state because of differing maintenance policies and severities of winter weather.

A countermeasure system can be a single element, such as heating cables, and it can contain more than one component, such as warning signs with deicing agents. The model must evaluate the benefit from any system, always compared to no special countermeasure.

It is essential to distinguish between the road surface conditions without countermeasures and those achieved with countermeasures. For instance, in the absence of countermeasures, ice or frost will form locally on bridges and approaches during some fraction of a year. With an ideal countermeasure. the formation would be prevented entirely, so that the fraction of a year with ice or frost is zero. Similarly, it is desirable to include an accurate account of countermeasures that are partially effective and are subject to error, failure, or delay. Consequently, one must provide for countermeasure systems that:

1. Reduce (or increase) the accident rate without removing localized frost and ice.
2. Normally eliminate local ice and frost, but leave a

surface with less than ideal characteristics (e.g., wet or covered with abrasives). Also, the possibility must be accounted for that these conditions will persist longer than the icy and frosty conditions would have in the absence of the countermeasure.

3. Normally detect and/or eliminate localized ice and frost, but fail temporarily or occasionally.

4. Occasionally change the surface condition unnecessarily through erroneous detection or prediction.

5. Produce a secondary benefit by early warning when the roadway is becoming *generally* icy, and in automatic systems treating one element, the bridge, without delay.

The comprehensive benefit model for localized bridge icing countermeasure systems can be written compactly as follows (see Appendix B for a detailed tabulation of the symbols used by the benefit model):

$$B = \sum_{m=1}^{5} T_m \left[R_m K_m - \sum_{n=1}^{5} P_{mn} (1 - A_n) R_n K_n \right] \qquad (2)$$

where:

B = annual dollar benefits of accident reduction resulting from application of the localized countermeasure system;

m, n = indexing numbers for bridge surface conditions that relate to vehicular traction, as follows:
- 1 = dry
- 2 = wet
- 3 = abrasives on ice
- 4 = localized ice or frost on bridge deck only
- 5 = generalized ice, frost, or snow

T_m = time, in hours per year, when a bridge surface is condition m without any localized countermeasures;

R_m, R_n = accident rate per hour of surface condition m or n;

K_m, K_n = average dollar cost per accident that occurred for surface condition m or n;

P_{mn} = proportion of time, T_m, converted to surface condition, n, by the localized countermeasure system; the condition $m = n$ describes the proportion of time, T_m, that the countermeasure system fails to change the surface condition; for any surface condition m, the sum of the P_{mn}'s $\sum_{n=1}^{5} P_{mn}$, must equal unity; and

A_n = proportion of accidents reduced for surface condition n by a localized countermeasure system (e.g., signing) that does not change the surface condition.

The first half ($T_m \cdot R_m \cdot K_m$) of Eq. 2 represents the cost of all accidents corresponding to road conditions in the absence of all specialized countermeasures. (Note that the sum $\sum_{m=1}^{5} T_m$ is simply the total time during which the condition would have been m without any special countermeasure.) The second half of Eq. 2 represents the reduction in benefits due to the costs of accidents still occurring after implementation of a countermeasure system. The coefficient, A_n, modifies the accident rate, R_n. It accounts for the fact that the rate may depend on factors other than the road surface condition. For example, a warning sign may not change the surface condition, but it may cause some motorists to be more cautious.

A countermeasure system could increase accident rates, during some periods. This possibility is accounted for implicitly through the term P_{mn}, and explicitly through the term A_n (see Appendixes B and H for further details).

The benefit model, therefore, requires four kinds of data:

1. Accident cost data for different pavement conditions.
2. Accident rate data for different pavement conditions.
3. Data on the duration of various road surface conditions.
4. Estimates of the effect of each particular countermeasure on road surface condition and its effect, A_n, on accident rate.

Countermeasures

Before considering the cost model, it is best to examine first the kinds of ice, snow, and frost countermeasures available to maintenance engineers.

Countermeasures may be broadly categorized as follows:

1. Those that attempt to control or modify the bridge deck condition—special pavement materials, techniques that prevent the formation of localized frost or ice, and techniques that affect removal of frost or ice in less time than is required by natural processes.
2. Those that warn the motorist of the hazardous condition—on-site signing that either warns of the possibility of localized frost or ice, or indicates that the condition currently exists, and communications media (radio, TV, or newspaper) that warn of the possibility of hazardous conditions.
3. Combinations of items (1) and (2).

The specific intent of the countermeasure study is threefold:

1. To identify available countermeasures.
2. To accumulate information on associated costs and operational characteristics (or effectiveness) for the cost and benefit models.
3. To indicate where additional cost and operational data are needed.

Data on countermeasures were assembled from published literature and from maintenance and cost accounting divisions of several state highway departments. Appendix G contains a summary of the major cost items together with other data needed by the cost model. In the following discussion, a general overview is given on the kinds of useful data available and the areas where data are lacking.

A countermeasure system may be either a simple, self-contained element, such as a permanent warning sign, or a combination of elements, such as deicing chemicals used in conjunction with plowing and blading. It is convenient initially to examine individual elements separately.

The principal countermeasure elements currently used are:

1. Plowing and blading.
2. Deicing chemicals.
3. Abrasives.
4. Salt spreading equipment.
5. Devices for bridge deck heating.
6. Warning signs.
7. Communications media.
8. Special pavement surface materials.
9. Bridge deck insulation (bridge deck insulation as a countermeasure has been shown to be ineffective in controlling localized ice and frost; it is included here only for completeness and will not be considered in the current study).

Plowing and Blading

Plowing and blading are the most commonly used measures to combat general ice and snow conditions. Often, they are used in conjunction with the application of deicing chemicals, which prevent or weaken the bonding action of ice and packed snow. In some rare instances, plowing and blading are performed only at bridges to remove localized ice or slush remaining after the bridge approach has melted. This particular countermeasure is included here for completeness, but it is not emphasized as a *localized* icing countermeasure.

Deicing Chemicals

Deicing chemicals are commonly used to remove ice or frost from bridge decks and highway pavement surfaces. Occasionally, they are applied in advance to prevent later formation of ice or frost. The most commonly used chemicals are salt or sodium chloride (NaCl) and calcium chloride ($CaCl_2$) because of their availability, favorable melting capabilities, and relatively low costs. These chemicals are used singly or in combination, depending on the particular weather environment. Alternate chemicals are occasionally employed. A recent study (*4*), for example, recommends mixtures of urea, calcium formate, and foramide because of their apparent reduced corrosive properties. Such materials are considerably more expensive than salt or calcium chloride and are rarely used on highways at present.

The amount of ice or frost that salt or calcium chloride will melt, given unlimited time, is known. The rate of melting has been determined in laboratory tests for straight salt, calcium chloride, and mixtures of the two. The melting rate is strongly dependent on the temperature of the ice and the mixture and on the amount of chemicals applied.

These known melting characteristics do not account for the effect of traffic on the ice removal process. Limited laboratory tests have been made of ice removal by a tire running over chemically treated ice. Field estimates have been made of the percentage of the ice cover that must be melted before it will be dispersed by traffic. Other (rough) field estimates have been made of the effect of traffic on the rate of ice removal. (These data on melting capability and rates and the effect of traffic provide a basis for estimating time histories of pavement conditions for use in the benefit model.) The important item to remember in accounting for the effect of deicing chemicals on localized icing conditions is that the chemicals are not applied with the intent of melting *all* the ice or snow. They are applied to facilitate plowing and to remove relatively thin layers of ice that can not be removed by plowing.

Atmospheric conditions (humidity, wind, etc.) and antecedent air temperatures also affect the ice removal rate. These effects have not been quantified, but they probably are not required for meaningful application of the benefit model.

The cost of salt and calcium chloride varies with geographical location. Bracketing estimates are available in the literature, and specific values have been obtained from highway departments of some states. Indirect costs associated with the use of deicing chemicals are incurred because of their corrosive effect on the reinforcing steel in the approach pavement and bridge deck. This phenomenon has been extensively investigated, and bases are available for estimating this additional cost.

Abrasives

Abrasives are used to increase the local friction coefficient. They are applied separately and also in combination with deicing chemicals. Friction coefficients have been measured for conventional abrasives (sand, cinders, crushed rock, etc.) for a wide variety of pavement conditions.

Estimates are available for the cost of conventional abrasives. Specific costs have been obtained from some state highway departments.

Salt Spreading Equipment

Salt spreading equipment falls into two categories: mobile and fixed. The mobile type is the one conventionally employed by the state highway maintenance departments. This type includes trucks and other equipment used to dispense salt and abrasives over sections of highways. The fixed spreader is mounted on a bridge railing or other parts of the structure; it dispenses salt over only a limited portion of the deck surface. The Hinrichs Deicer System was designed primarily for use with the latter type of automatically activated salt-spreading equipment.

Pavement Heating

Bridge-deck and approach-pavement heating is used to prevent or remove ice and frost. The most common modes of heating include:

1. Electrical—imbedded heating cables, imbedded wire mesh, conductive pavement materials, and conductive mats.
2. Warm fluids in imbedded pipes—gas-fired, oil-fired, and using subsoil as a heat source.

The operational characteristics of these various heating systems are described in considerable detail in the published literature. Heat requirements and melting capabilities have been observed in a large number of field installations in pavements, and to a lesser extent, in bridge decks.

Installation and operating costs are also provided in the literature. The costs associated with the heating systems depend on the energy source and geographical region (see Appendix G). Generally speaking, the operating costs are considerably higher than those associated with chemical deicers. Very few definitive data are available on either maintenance costs for the heating systems or their effect on the life of pavement materials.

Other less conventional and largely unexplored heating methods include: overhead infrared devices, infrared sources and gas-fired warm air sources in enclosed areas under the bridge deck, open-flame portable devices, and the use of nuclear waste as a heat source. (Dynatherm Corporation, under FHWA Contract FH-11-7413, is doing a study entitled, "Nuclear Wastes in Comparison with Other Heat Sources for Deicing of Bridges, Ramps, and Pavements.") Very little is known about costs and operational characteristics of these methods.

Warning Signs

Two kinds of signs are employed; namely, those displaying a permanent warning message and those which can be lighted, unfolded, or otherwise activated for temporary periods, including variable-message signing.

The effectiveness of warning signs is largely unknown. A recent research review by MRI on the response of motorists to warning signs, in general, led to the conclusion that most drivers do not respond as desired. Reasons for the failure to comply are postulated and suggestions are given on how compliance might be improved. An icy-bridge warning-sign experiment conducted locally as part of the same contract confirmed the general conclusion.

Data are available on initial costs and service life of conventional highway signs. Initial costs of variable message signs can be obtained, but data on maintenance costs are unavailable.

Communication Media

General warnings are often issued on the possibility of icy bridges in newspaper notes and regular radio and TV weather reporting. Approximate costs could be estimated, but the impact of such warnings is unknown. Interest in applying the cost and benefit models to this kind of countermeasure is unlikely.

Special Pavement Materials

Special skid-resistant surfaces are sometimes used on bridge decks for increased traction under unfavorable weather conditions. Application cost and wear-life estimates are available for a variety of these surfaces, but their ability to counteract the hazard created by frost and thin ice coatings is not known. At best, only highly subjective evaluations have been made.

The Cost Model

A cost model is used to calculate the dollar value spent or scheduled to be spent to achieve a net benefit from a countermeasure system. The model developed consists of a number of submodels and is quite detailed in its scope of coverage. The cost model is presented in detail in Appendix F; an overview and listing of its components are given here.

Costs can be of three types: initial costs, annual costs, and periodic costs. The periodic costs are usually associated with repair or replacement. Since all of these costs may be important, but do not occur concurrently, the cost model necessarily accounts for the time value of expenditures.

The cost model includes only those costs incurred by the countermeasure system for localized frost, ice, and snow; it does not include those costs that would have occurred without the system or any of its components. Also, a countermeasure system may simply increase the frequency of an existing, periodic cost. Only the marginal increase should be included in the model. Where a system component is shared by other activities (e.g., a radio communication system), the model should reflect a prorated cost.

A localized ice, frost, and snow countermeasure or maintenance system can consist of three phases, each of which may involve costs. These are detection or prediction, countermeasure agents, and repair activities necessitated by the countermeasure. Obviously, some systems may not require the repair costs. Also, a great variety of techniques or physical components are possible in any of the three phases, and numerous combinations may be employed.

Therefore, it is best to deal with submodels or modules that can be costed essentially independently and later assembled. This is the approach adopted here. In the following, each of the submodels developed is listed, together with its primary constituent parts; the actual cost equations are reserved for Appendix F.

1. Detection and Prediction—
   a. Communication system (owned): initial cost, maintenance and operating costs.
   b. Communication system (leased): annual lease rate.
   c. Facility watches (monitoring): number, cost per watch.
   d. Meteorological instrumentation: power, initial cost, maintenance and operating costs.
   e. Weather service: annual cost.
   f. Special patrols: number, distance, speed, driver pay rate, vehicle cost per mile, make-ready and cleanup costs.
   g. Sensor systems: initial cost, installation cost, engineering costs, maintenance and operating costs, deck life, sensor life.
   h. Logic circuitry: power, on-site wiring, initial cost, maintenance and operating costs, engineering costs.
2. Countermeasures—
   a. Fixed signing: initial cost, maintenance cost, engineering costs.
   b. Optional display signing: power, initial cost, installation costs, maintenance and operating costs, engineering costs.
   c. Pavement heating system: initial cost, installation cost, paving and repaving costs, special wiring,

power, maintenance and operating costs, deck life, heater life, engineering costs.

d. Deicing chemicals or abrasives: purchase cost, transportation costs, handling and mixing costs, storage costs, rework of remnants.

e. Spreading: make-ready and cleanup costs, number of trips, distance traveled, speed, driver pay rate, vehicle cost per mile, spreading equipment costs.

3. Repair and Maintenance Costs—Bridge deck maintenance, pavement life, scale (limited life), spall (limited life), repair or resurface life, cost for scaling repairs, cost of linseed oil treatment, cost of sealing coat, cost of deck replacement.

Benefit/Cost Ratio

Once the benefit model has been assembled and evaluated and the cost equations worked out, the benefit/cost ratio may be calculated. These analyses commonly use a consistent technique in allocating costs and benefits over a substantial time span.

First, all costs and benefits are expressed as average annual dollars. Although most economists anticipate continued inflation as a long term prospect, the inflation rate is unforeseeable. However, a useful result will still be obtained, because both costs and benefits are calculated on the same basis.

Second, money held or applied over a period of time has value in addition to its initial worth. This added value is defined by the interest rate. Once the time span of the system is ascertained, and the benefit and the cost models worked out, the discounting calculations should be applied to each model. (Normally, the assumption that the annual benefit is constant over the years is sufficient; however, if substantial traffic increases or decreases are envisioned, the accident rates and benefits should be modified accordingly.) Then, the simple ratio is calculated.

Finally, it may be of interest to compute a net cost (or benefit) of the system. This is simply the difference between (rather than ratio of) benefit and cost.

A State Net Cost Model

Highway maintenance activities help make travel for the public both safe and convenient. (The "value" of providing convenience to the motoring public, although important, lies outside the scope of the present report.)

The safety aspects, measured by reduction in accidents, have already been discussed, and are represented by the benefit model. That model, through cost factors, yields a dollar savings in accidents as a result of special countermeasures for localized ice and snow. The savings accrue to society at large, of course, rather than directly to the state highway department or even the state *in toto*.

It may be desirable to examine the net cost to a state for its maintenance activities, by accounting for that portion of the savings that apply to the state. Or, stated differently, one could account for state costs that would not occur because of a reduction of accidents attributed to localized countermeasures. These are not costs in addition to those in the benefit model; rather, they are a part of the accident costs included there, but looked at in a different way. (The dollar benefits in the benefit model arise from a reduction in accidents. In turn, dollar values are placed on property damage, injuries, and human life. The last two include such factors as loss of anticipated earnings, which may or may not be recovered through insurance, welfare, or legal judgments.)

Several examples of such costs (cost savings) can be cited. For example, consider the following:

1. Damages to state property not recoverable through insurance.
2. Confinement in state-supported hospitals or medical costs paid for by the state.
3. Welfare payments to families of persons killed or disabled in automobile crashes.
4. Legal defense and liability judgments against the state.

These costs are similar, in that they all result from crashes, can be lessened as crash frequency is reduced, and are paid by the state. The defense and liability (D&L) costs are examined in more detail, as follows; any of the others can be handled in a like manner.

The D&L costs should be incorporated in a net cost model as a "D&L cost change," which is given by the difference between D&L costs with a countermeasure system and D&L costs without the specialized countermeasure. For effective countermeasure systems, this difference is negative. The analytical form of the D&L costs will bear a significant resemblance to the benefit model.

Assume the possibility that a suit against the state can arise from any accident on a bridge, overpass, or approach (irrespective of road surface conditions) and, further, that the probability of a suit will depend on the accident severity and the condition of the road surface at the time of the accident. Thus, S_{in} equals the probability that a suit will be brought against the state in a bridge accident severity type, i, which occurred with pavement condition, n. (Note that the model includes the possibility of accidents (and claims) resulting from a countermeasure. For instance, application of a salt brine for preventive purposes may be represented as resulting in a special pavement condition.)

When a suit is brought, the state will incur expenditures for legal services, and the magnitude of these services will depend on the accident severity (and therefore magnitude of the claim), and also on the conditions of the road surface. Thus, L_{in} equals the average legal costs to the state arising from a suit for a bridge accident of severity, i, on road surface condition, n.

Next, define P_{in} as the probability that the suit against the state will be successful (in or out of court) with dependence on severity, i, and road surface condition, n; also define J_{in} as the average judgment or claim collected from the state for bridge accidents of severity, i, and road condition, n (this includes court costs, if any). Thus, the average cost to the state in legal services and judgments can now be written for *each* bridge accident with severity, i, and road condition, n:

$$\text{Cost} = S_{in}(L_{in} + P_{in} J_{in}) \qquad (3)$$

It is emphasized that P_{in} is the probability of success for the claimant after a suit or claim has been brought. The S_{in} is the probability that a suit or claim will be brought for each accident of severity i and road condition n. Note also that costs can be incurred with no successful claimants.

The yearly D&L costs for a bridge or set of bridges can now be written

$$\text{Cost} = \sum_{m=1}^{M} T_m \left[\sum_{n=1}^{N} P_{mn} \sum_{i=1}^{I} (1 - A_{in}) R_{in} S_{in} (L_{in} + P_{in} J_{in}) \right] \quad (4)$$

where:

T_m = the time, in hours per year, when the surface is condition, m, without any countermeasures;
P_{mn} = proportion of time, T_m, converted to surface condition, n, by the countermeasure;
A_{in} = a coefficient for the ith type accident frequency under surface condition n, applied to account for effects of the countermeasure beyond that of simply modifying the surface (most $A_{in} = 0$); and
R_{in} = accident rate of severity i accidents on bridges and overpasses that have surface condition, n, in accidents per hour.

Figure 1 shows how the annual D&L costs will depend on the effectiveness of a countermeasure system. The D&L cost associated with the ideal system arises from those accidents that would occur if an ideal (dry and clean) pavement condition were provided all the time.

From the costs given in Eq. 4 must be subtracted the costs that would occur without the specialized countermeasure system. These costs are

$$\text{Cost} = \sum_{m=1}^{M} T_m \left[\sum_{i=1}^{I} R_{im} S_{im} (L_{im} + P_{im} J_{im}) \right] \quad (5)$$

The character of the D&L cost change is shown in Figure 2.

The D&L change is negative for a countermeasure system that is effective. This negative quantity is to be added algebraically to the previously presented cost model to obtain the net cost to the state of implementing a localized countermeasure system.

The question arises, can the D&L costs be incorporated in a benefit/cost model? An analysis suggests that they not be treated in this way. In a sense, D&L costs (as well as other state-borne costs such as medical or welfare payments) are already included implicitly as a part of the total costs (to the public) of accidents. Conceivably, one could separate these elements from the benefit model and deal independently with them in a cost/benefit model. One then is faced with a second question, are they benefits or costs?

The D&L and other costs can be incorporated in either the cost model or the benefit model. Opinion is divided on which is better, because either approach has advantages and disadvantages, as itemized in Table 2.

To summarize, it appears that when a cost-benefit analysis is made, the benefit model of Eq. 2 (which includes all benefits to society) and the cost schedules of Appendix F should be used. On the other hand, if a state wishes to analyze its net expenditures for specialized maintenance activities, the cost schedules of Appendix F must be reduced by the savings to the state in D&L (and other) costs.

BRIDGE CLASSIFICATION MODEL

The goal of this phase was to demonstrate the construction of a mathematical model for predicting the annual number of ice and snow accidents on a bridge, given various characteristics of the bridge. The technique, although designed with the aid of accident data, should be capable of application to bridegs not yet showing a significant accident history.

Initially, the intent of the project was to use a multiple regression model for this purpose, patterned after the work of Cirillo et al. (*5*). That work was aimed at estimating the number of accidents occurring on road sections with common geometrics, such as different types of interchanges, bridges, or special lanes. A multiple regression model was used, yielding number of accidents as a function of a variety of traffic, terrain, and roadway features.

Candidate features for the proposed model were selected and the basic regression model was formulated. However, adequate data were extremely difficult to obtain.

At this point the entire regression approach was reevaluated and discarded. Fundamental to this decision was that icy bridge accidents are extremely rare events. As an

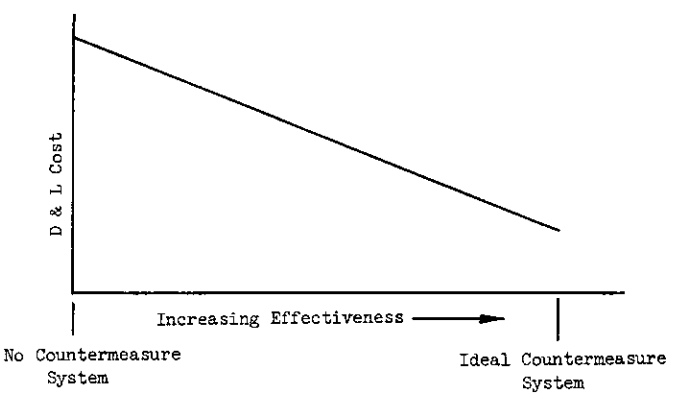

Figure 1. D&L cost versus effectiveness.

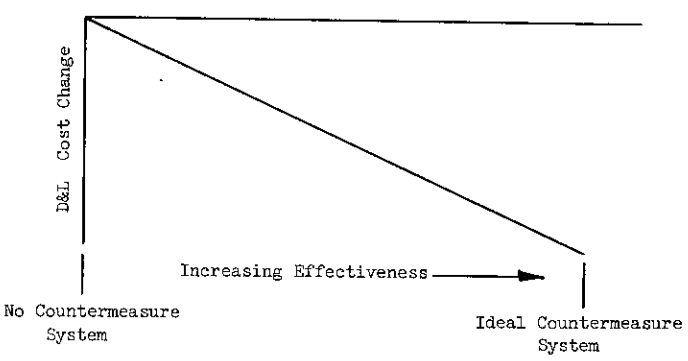

Figure 2. D&L cost change versus system effectiveness.

TABLE 2

CONSIDERATIONS FOR INCORPORATION

Model	Quantity to be Added (Algebraically) to Model	Comments
Cost	D & L cost change = (D & L yearly costs with countermeasure system) - (D & L yearly costs with no countermeasure system	Advantages - Incorporation in the cost model is desirable in that benefits remain homogeneous and consist of reduction of accident costs which directly benefit highway users. Also, the D & L costs are items which appear in the state budgets like other costs.
		Disadvantages - It is undesirable that for an effective countermeasure system the "D & L cost change" will be negative. If this item is large (negative) it could reduce total costs toward zero and exaggerate the benefits/cost ratio. Also, the "D & L cost change" is not a budget item but the difference between two possible budget totals.
Benefit	D & L cost benefits = (D & L yearly costs with no countermeasure system) - (D & L yearly costs with countermeasure system)	Advantages - Incorporation in the benefit model is desirable in that the quantity added is positive for an effective countermeasure system. Also, the logic of calculating this benefit is generally consistent with the cost reduction logic applied to accidents. This incorporation cannot disrupt or exaggerate the ratios employed.
		Disadvantages - It is undesirable to make the benefits inhomogeneous, especially since accident reduction benefits go directly to the highway users while D & L benefits will appear first at the state budget. Also, the D & L cost benefits are not a budget item but the difference between two possible budget totals.

estimate, only one such accident occurs for every 10 to 30 bridges in a year. (This pinpoints the very need for a bridge hazard model.) That the annual accident experience for an average bridge is nearly always zero leads to practical and theoretical problems in quantifying a regression model. These problems are covered in Appendix I.

An alternate method was devised in building a discrete bridge model rather than a continuous one. The model is essentially constructed from Bayes' Rule, and uses available accident statistics and bridge characteristics to estimate the probability of a nonzero number of ice and snow accidents per year for a bridge. This probability is then used to predict the expected number of ice and snow accidents per bridge per year under the usual Poisson assumption.

The bridge classification model is described in detail in Appendix I. The model requires the knowledge of seven bridge variables, a table of computed probabilities, and a simple calculation. The seven bridge parameters are:

1. Average daily traffic.
2. Over-all length (feet).
3. Roadway width (feet).
4. Location (rural or urban).
5. Crossing type (water or other).
6. Highway type (divided or undivided).
7. Structure type (concrete or other).

In general, a state or locality should develop its own set of probabilities for icy and snowy conditions following the procedure of Appendix I. Also, to consistently make use of the bridge model, the agency should develop an additional set of probabilities each for wet and dry pavement conditions. An application to Ohio of the model for icy and snowy pavement conditions is included in Chapter Three under "Application of Bridge Classification Model."

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION OF FINDINGS

APPLICATION OF COST-BENEFIT METHODOLOGY TO SELECTED CASES

The application of the cost-benefit methodology to practical ice, frost, and snow removal maintenance systems was demonstrated by six numerical examples. The examples chosen illustrate various combinations of detection and/or prediction systems, various types of countermeasures, and the side effects and cleanup associated with the countermeasures. In addition, four of the examples were applied to different regions of the United States to illustrate geographical variations. Used in the examples were data collected throughout the study and also subjective values, based on engineering judgment, of those parameters for which little or no information was available. The details of the numerical examples are presented in Appendix H. A summary of the results is given as follows.

The first example consists of installing frost and ice detectors on a group of bridges with like characteristics considered potentially important. The detectors are used solely to activate motorists' warning signs located near the bridges. No other specialized countermeasures, such as maintenance alerting, were included in this example. Two sets of bridges are considered: (1) 40 pairs of Interstate bridges in the southcentral portion of Iowa, encompassing Des Moines, denoted by Example A in Appendix H, and (2) a group of 27 bridges which have had accident experience in the northeastern portion of Ohio, including Youngstown, denoted by Example B.

The second example demonstrates the results of applying the bridge classification model to the same group of Ohio bridges used in the first example (Example B). Frost and ice detectors are again installed on the bridges and used to activate motorists' warning signs located near the bridges. No other specialized countermeasures are included. Two sets of bridges are considered: (1) all of 27 bridges which have had accident experience, denoted by Example C, and (2) the top nine of the 27 bridges arranged in a descending order according to the predicted number of ice and snow accidents, denoted by Example D.

The third example illustrates the evaluation of two alternative countermeasure proposals considered for a specific bridge location. A pair of bridges on I-95 at the interchange with Route 1, near Spotsylvania, Va., is selected as a sample location. This location has a high accident history and represents a type that might be singled out for individual treatment. One countermeasure proposal (Example E) involves installing a frost and ice detection system on the twin bridges. The detectors are used to activate nearby motorists' warning signs. The second countermeasure proposal (Example F) consists of a prediction/detection system coupled to a pavement heating system installed in each bridge deck.

The fourth example consists of an areawide system. Detection is accomplished through utilization of existing state highway police patrols, who are asked to report localized icy bridges to the local highway maintenance area. Each area is manned by a watchman, who also has other duties to perform. On alert, the watchman summons crews, who then patrol their assigned route sections and spread deicing chemicals as required. Three geographical regions of the country are selected as representing moderate, heavy, and light amounts (exposure times) of hazardous winter weather conditions. These regions are south-central Iowa (Example G), northeast Ohio (Example H), and the Texas Panhandle (Example I).

The fifth example is similar to the fourth, except that frost and ice detectors are used instead of relying on state police patrols. The watchman in the fourth example is replaced by a radio receiver in the home of the resident maintenance engineer or his foreman. Each maintenance area instruments two bridges as indicators for the area, and all maintenance areas are assumed to be in communication via an existing maintenance radio frequency network. The same three geographical regions of the fourth example are again used.

The sixth example is similar to the fifth, except, on alert of localized icing conditions, the maintenance crews are dispatched to spread noncorrosive deicing chemicals on all the bridges. Bridge deck deterioration costs included in the fourth and fifth examples are omitted in this example. The three geographic areas are again used as illustrations.

The annual dollar benefits and costs and benefit/cost ratios computed for each example are given in Table 3. All annual costs presented are computed using a 6 percent interest rate and the system life shown in the table. The maximum benefit possible for each system was computed by considering an ideal system that is 100 percent effective in eliminating all accidents under localized icing conditions; accidents under other pavement conditions are still possible and accounted for. The localized icing times prevented or eliminated by the ideal system were distributed among wet and dry pavement conditions according to the assumptions imposed in each example.

The percent effectiveness is a measure of over-all system effectiveness in reducing the number of accidents under localized icing conditions. These percentages are determined by ratioing the benefit to the maximum benefit possible. The least effective system (39.5 percent) is the detector-motorist warning sign combination, whereas the most effective system (87.0 percent) is the predictor/

TABLE 3

SUMMARY OF RESULTS FROM APPLICATION OF COST-BENEFIT METHODOLOGY TO SELECTED CASES

Example	Location	Maintenance System	System Life (years)	Annual Benefit, B ($)	Maximum Annual Benefit, B_{max} ($)	Percent Effectiveness of System	Annual Cost, C ($)	B/C	B_{max}/C
A	All interstate bridges in South-Central Region of Iowa	Frost and ice detectors activate motorist warning signs	10	19,600	49,620	39.5	41,200	0.48	1.20
B	27 bridges in North-Eastern Region of Ohio	Same as A	10	10,490	26,555	39.5	13,900	0.75	1.91
C	27 bridges in North-Eastern Region of Ohio	Same as A	10	11,860	30,025	39.5	13,900	0.85	2.16
D	9 of the 27 bridges in North-Eastern Region of Ohio	Same as A	10	9,795	24,800	39.5	4,635	2.11	5.35
E	I-95 bridge over Route 1, Spotsylvania, Virginia	Same as A	30	1,750	4,430	39.5	770	2.27	5.75
F	I-95 bridge over Route 1, Spotsylvania, Virginia	Prediction/detection system activates electric pavement heating	30	5,825	6,695	87.0	5,285	1.10	1.27
G	All bridges in South-Central Region of Iowa	State police patrol alert maintenance watchman who dispatches maintenance patrol crews to spread deicing chemicals (chlorides)	50	34,505	69,005	50.0	59,520	0.58	1.16
H	All bridges in North-Eastern Region of Ohio	Same as G	50	9,655	19,310	50.0	24,585	0.39	0.79
I	All bridges in Panhandle Region of Texas	Same as G	50	15,490	30,975	50.0	86,165	0.18	0.36
J	All bridges in South-Central Region of Iowa	Warnings from frost and ice detectors transmitted to maintenance foreman who dispatches maintenance patrol crews to spread deicing chemicals (chlorides)	50	57,870	85,475	67.7	80,920	0.72	1.06
K	All bridges in North-Eastern Region of Ohio	Same as J	50	16,155	23,880	67.7	31,005	0.52	0.77
L	All bridges in Panhandle Region of Texas	Same as J	50	26,625	39,015	68.2	104,355	0.26	0.37
M	All bridges in South-Central Region of Iowa	Same as J except maintenance patrol crews spread noncorrosive deicing chemicals	50	57,870	85,475	67.7	83,905	0.69	1.02
N	All bridges in North-Eastern Region of Ohio	Same as M	50	16,155	23,880	67.7	32,425	0.50	0.74
O	All bridges in Panhandle Region of Texas	Same as M	50	26,625	39,015	68.2	119,395	0.22	0.33

detector pavement heating combination. An improvement in effectiveness can be obtained over a maintenance system employing state police as a detection element by using detection devices coupled to an automatic alert system. The associated costs are greater, however. The magnitudes of the effectiveness values might be subject to some question and must be interpreted in terms of the assumptions used in each example. However, the relative ordering of these values, in going from the simpler system to the more complex, areawide systems, appears to be reasonable.

A number of interesting results are given in Table 3. The benefit/cost ratio (B/C) values range from a low of 0.18 to a high of 2.27. All of the B/C values associated with the areawide grouping of bridges (examples 4, 5, and 6) are less than unity (the break-even point). The lowest B/C values are obtained from an areawide grouping of bridges in the Texas Panhandle. Half of the B/C valeus obtained from the cases of selected bridges (examples, 1, 2, and 3) exceed unity. All of the theoretically maximum ratios from the selected bridges are larger than unity. However, the B_{max}/C values for the areawide grouping of bridges, other than those in Iowa, are less than unity.

Bridge-deck deterioration costs attributed to localized icing conditions are incorporated in examples 4 and 5. These costs are a small portion of the total costs (12 to 17 percent). For a given countermeasure system, the fraction of the total cost due to deterioration is virtually independent of geographical consideration. In example 4, the fraction ranges from 14 to 17 percent and is about 12 percent in example 5. A maintenance system employing an expensive noncorrosive deicing chemical (example 6) will not necessarily yield a higher B/C value than a corresponding system (example 5) in which relatively inexpensive chlorides are used and bridge-deck deterioration costs are incurred.

In assessing the low magnitude of the B/C ratios for the areawide grouping of bridges and some of the selected bridge cases, it would be beneficial to compare them to the benefit/cost ratio for winter maintenance activities on the state highway system as a whole. Although this is not entirely possible, some estimates can be made.

For example, consider the State of Iowa, wherein approximately 10,000 miles of roadway are under state winter maintenance ice and snow control (total highway system in salting program). Most of these road miles are in rural areas. In 1969, Iowa experienced 34 fatal accidents, 1,355 injury accidents, and 5,019 property-damage-only accidents under snow or icy pavement conditions on the rural highway system (*6*). These include, as a subset, the bridge accidents discussed in Appendix C. The maximum yearly benefit that could be achieved by eliminating all of the foregoing accidents, using the accident costs in Table D 3, is $12.3 million. This is the value of the accidents *not* prevented by current maintenance practices. Iowa's total maintenance expenditures during that year were about $23.4 million (*7*). It is reasonable to assume that snow and ice control could have amounted to about half of this amount, or $11.7 million. (In Ref. (*3*) it was reported that about 48 percent of the annual maintenance budget of the New England States was expended on snow and ice control; this does not include costs associated with repair or replacement of salt-damaged bridge decks.)

If a perfect countermeasure system costing this amount (i.e., resulting in doubling the winter maintenance budget) could be developed to eliminate *all* of these accidents, a benefit/cost ratio of only slightly larger than unity (B/C = 1.05) would be obtained. In actuality, the expenditures required to eliminate all of the snow or ice accidents could easily be two to three times the $11.7 million spent, so that the resulting B/C value would be much less than unity.

These values, crude as they are, indicate that winter maintenance activities in general may not be cost beneficial from an accident reduction standpoint. In fact, it is possible that without the current fine work being done by state highway departments, traffic would slow markedly, often become completely stopped; volumes would fall off; and perhaps accidents would decrease or at least tend to be of a less serious nature. Clearly, if one attempts to make a cost/benefit analysis using no maintenance as a basis, a low (or perhaps even negative) benefit from reduced accident costs may result. To justify general winter maintenance activities, then, requires a much broader definition of benefits, including a value judgment of the services to the citizens provided by maintaining a bare pavement most of the time. In other words, a benefit/cost ratio based solely on accident reduction should not necessarily be expected to be large compared to unity.

The examples of the cost-benefit methodology application presented are for illustrative purposes only. They are only a sampling of the many countermeasures possible and are not necessarily the best solutions to a particular problem. The types of preventive and remedial countermeasure techniques used in the examples were selected on a rational basis using engineering judgments. A highway administrator interested in determining the optimum countermeasure for the localized icing problem would need to evaluate the B/C values for each competing countermeasure proposal and then to compare the results.

The evaluation of two competing countermeasure proposals is illustrated in the third example. Based on the assumptions used, the detection-motorists' warning sign system in Example E would be favored over the predictor/detector pavement heating system in Example F. The B/C and B_{max}/C values for Example E are about twice and 4.5 times as large, respectively, as the corresponding values for Example F. Also, the annual cost of the maintenance system in Example E is about one-seventh the annual cost of the system in Example F.

One must be careful in comparing the B/C values obtained from an areawide grouping of bridges (examples 4, 5, and 6) with those values obtained from selected bridges (examples 1, 2, and 3). Entirely different techniques (countermeasures) were used in the examples, with greatly differing costs and approaches to the problem. Each example countermeasure system was tailored to the problem.

Perhaps a better comparison between the results obtained for the areawide grouping of bridges and selected bridges can be found by looking at the expected yearly benefit/bridge. In Appendix H, the annual benefit/bridge for the first three examples ranges from $245 to $5,825, compared

to a range of between $15 and $64 for examples 4, 5, and 6. Annual costs exceeding these values produce B/C values less than unity. Even though the value $245 seems to be an extremely low annual benefit, it is almost four times the largest annual benefit/bridge found for areawide groupings of bridges.

Some of the most significant findings in Table 3 concern the results of applying the bridge classification model (discussed in the following section) to a group of bridges in the northeastern region of Ohio (example 2). The annual benefit/bridge and benefit/cost ratios computed for Example C compare favorably with the values computed for Example B: $439 and 0.85, respectively, for Example C as opposed to $388 and 0.75 respectively, for Example B. The annual benefit/bridge and benefit/cost ratios computed for the nine selected bridges in Example D are $1,088 and 2.11, respectively. These values are about two and one-half times larger than the results found for the 27 bridges in Example C. In addition, the value $1,088 is 60 times larger than the annual benefit/bridge of $18 for the areawide grouping of bridges in Example H.

These results point out the fact that higher annual benefits/bridge can be obtained by selectively choosing bridges for improvement, through use of a bridge classification model, rather than by treating areawide systems of bridges. However, the bridge classification model will still not guarantee a benefit/cost ratio greater than unity for many countermeasure proposals.

APPLICATION OF BRIDGE CLASSIFICATION MODEL

The model developed in Appendix I and summarized in Chapter Two was applied to a portion of Ohio. Bridge accident data and bridge logs were available from seven maintenance divisions of the Ohio Department of Transportation. Of the 6,305 bridges in these divisions, 155 experienced one or more ice and snow accidents during a 2-year period. These "bad" bridges and a sample of 203 "good" bridges (one that had no ice or snow accidents during the same period) were used to compute seven sets of probabilities needed by the model. The results are given in Appendix I.

It should be emphasized that the tabulation of the probabilities given in Table I-1 for the seven bridge parameters is really only applicable to bridges in an environment and under maintenance practices like those in Ohio. They may be used for comparative purposes or for performing preliminary computations, but it is strongly recommended that a state develop and use its own set of probability values.

To illustrate the technique, the bridge model was applied in two ways to a sample of bridges used in several of the cost-benefit examples described in Appendix H. This sample consists of a group of 27 bridges which have had accident experiences in the northeastern portion of Ohio. The set of 27 bridges represents a total of 36 accidents: 15 under ice and snow conditions, 7 under wet pavement conditions, and 14 under dry pavement conditions. Table 4 displays the results of applying the model to the set of bridges. The bridge model predicts a total of 16.95 ice and snow accidents versus 15 actual. The value of 16.95/27 is theoretically a better estimate of the ice and snow accident rate than the value 15/27 used in the example. Of course, in order to consistently make use of the bridge model in combination with the cost-benefit methodology, a bridge model would be needed for wet and dry pavement conditions. In the set of 27 bridges, chosen because they experienced a recent accident of some kind, nine of them had a predicted total number of ice and snow accidents of 14.00, 83 percent of the total. Thus, the "top" one-third of the sample contains 83 percent of the expected ice and snow accidents; or, equivalently, the top nine bridges have an ice and snow accident rate almost two and one-half times greater than the accident rate for the whole set. This illustrates the increase in the benefit/cost ratio available by using the bridge model.

CHAPTER FOUR

CONCLUSIONS AND RECOMMENDATIONS

Several conclusions have been drawn from this study. Some of these conclusions should be considered as tentative until more detailed testing of the models has been performed and additional data have been collected.

Within these limitations, the conclusions are as follows:

1. A comprehensive cost-benefit methodology has been developed for the economic evaluation of the effects of ice and frost on bridge decks. The applicability of the methodology to practical situations is demonstrated by example cases.

2. No concerted effort has been made by the states to collect records either on the frequency of occurrence and duration of localized ice and frost or on the susceptibility of certain types of bridges to localized icing in relation to their operating environment (including topographical, meteorological, traffic and maintenance operation). Some frost frequency data are available from special studies conducted in California and Kansas.

3. Special winter maintenance data forms were developed and successfully used to collect records on the fre-

TABLE 4

BRIDGE CLASSIFICATION MODEL APPLIED TO 27 OHIO BRIDGES

Bridge Rank	Bridge Number*	Bridge Characteristics X_1,	X_2,	X_3,	X_4,	X_5,	X_6,	X_7	Expected Number of Ice and Snow Bridge Accidents per Year	Number of Accidents Actually Recorded: Ice, Snow	Wet	Dry
1	MED-071-1569	5	5	4	2	2	2	1	1.5795		1	1
2	MED-071-0031	5	5	4	2	2	2	1	1.5795	1		
3	MED-071-0437	5	5	4	2	2	2	1	1.5795	1		
4	MED-071-0729	5	5	4	2	2	2	1	1.5795		1	
5	MED-071-0794	5	5	4	2	2	2	1	1.5795	2		
6	MED-071-0860	5	5	4	2	2	2	1	1.5795	1		
7	MED-071-1450	5	5	4	2	2	2	1	1.5795	1		
8	MED-080-0158	5	5	3	2	2	2	1	1.5434			1
9	MED-071-2090	4	5	4	2	2	2	1	1.4021	1		1
10	POR-044-1805	4	5	3	1	2	2	1	0.6921	1	1	1
11	POR-043-1375	4	5	1	1	2	2	1	0.5426		1	1
12	POR-088-0903	3	5	3	1	2	2	1	0.4530		1	
13	MED-071-1992	4	5	4	2	1	2	1	0.4234			1
14	TRU-005-0657	5	5	2	1	2	2	1	0.3642	1		
15	MED-071-1918	4	4	4	2	2	1	1	0.2259			1
16	MED-071-0060	5	4	4	2	1	1	1	0.0534	1		
17	MED-071-0539	5	4	4	2	1	1	1	0.0534	1		
18	MED-303-0251	3	5	5	1	1	2	1	0.0473	1		
19	POR-082-1067	3	5	2	1	1	2	1	0.0339	1		
20	MED-421-0049	3	4	1	1	1	2	1	0.0229			1
21	MED-042-0460	4	4	5	1	1	1	1	0.0212		1	2
22	TRU-304-0389	4	2	1	1	1	1	1	0.0051			1
23	MED-303-0110	3	2	1	1	1	1	1	0.0030	1		
24	TRU-087-0425	2	3	1	1	1	1	1	0.0018		1	1
25	TRU-534-1517	2	3	1	1	1	1	1	0.0018	1		
26	TRU-534-2546	2	2	1	1	1	1	1	0.0018			1
27	MED-042-1821	5	1	5	1	1	1	1	0.0009			1
									16.9461	15	7	14

* Bridge number is defined in terms of county, route and mileage from the west or south boundary of the county depending upon the primary orientation of the route within the state. The counties included in this table are MED - Medina, POR - Portage, and TRU - Trumbull.

quency of occurrence and duration of localized ice and frost. A state wishing to collect localized bridge deck icing data for a specific area can do so using the forms developed.

4. It is difficult, using existing state records, to estimate treatment costs of localized ice and frost and also the increased costs of bridge maintenance and repairs due to the application of deicing chemicals. Some data are available, however, in areas where only localized conditions occur.

5. The accident reporting forms used by most states are not specific enough to note the occurrence of bridge accidents under localized icing conditions. The "frosty" bridge accident data that exist are generally extracted by data encoders from comments and remarks noted by the investigating law enforcement officers. However, completeness and/or validity of this information is questioned because of the lack of uniformity in recording the data.

6. Extreme care must be exercised in assembling and analyzing bridge accident data. In many localities an accident is classified as a bridge accident only if part of the bridge were struck, thus missing many accidents occurring on, or contributed to by, a bridge. This may help explain why so few fatal bridge accidents under ice or snow conditions are recorded.

7. Special bridge accident data were successfully collected by state highway patrols on a sampling basis, using a data form designed to supplement the standard accident report. Of the ice and snow accidents recorded in the sample, 43.2 percent occurred under localized conditions.

8. Most of the benefit/cost ratio values obtained from use of the methodology for areawide groupings of bridges will probably be less than unity. The benefit model is based solely on safety considerations, not service to the public. Thus, the methodology for these systems of bridges can best be used to compare countermeasure proposals and not to justify costs.

9. A maintenance system employing an expensive noncorrosive deicing chemical will not necessarily yield a higher B/C value than a corresponding system in which relatively inexpensive chlorides are used and bridge deck deterioration costs are incurred.

10. A bridge classification model was constructed that will provide guidance in the identification of those bridges or classes of bridges most in need of treatment for bridge deck icing problems. The model results are used to predict the annual number of ice and snow accidents on a bridge, given various characteristics of the bridge.

11. Higher annual benefits/bridge can be obtained if one selectively chooses bridges for improvement through use of a bridge classification model rather than if one treats areawide systems of bridges. However, the use of a bridge classification model will still not guarantee a benefit/cost ratio greater than unity for a range of countermeasure proposals.

These conclusions have inherent recommendations that form the basis for future work. The over-all recommendation is that the cost/benefit methodology developed be applied by those states interested in determining the economic evaluation of the effects of ice and frost on bridge decks. The results of this study provide the highway administration with sufficient tools to help evaluate the magnitude of the localized icing problem for his state and also to determine the most appropriate countermeasure solution(s) for his needs.

Each interested state can assemble, with a minimal amount of data collection, the information necessary to apply the models within specific geographic constraints. Possibly the most important data the state needs to collect are special winter maintenance data and reliable bridge accident data. Both of these data can be collected by using the approaches discussed in this report. The special winter maintenance data are needed to help establish the frequency and extent of localized bridge deck icing. The special bridge accident data are required by the state to construct its own bridge classification model for each of the desired pavement conditions.

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APPENDIX A

DETAILS OF STATE VISITS

A brief description of the results of visits in each of nine states (1970-1971) is presented in this appendix. The discussions with representatives of the highway and transportation departments in the nine states proved extremely beneficial not only in ascertaining the availability of certain types of data, but also in providing basic background information useful in the development of the models presented in this report.

ARKANSAS

Arkansas does not have a written maintenance manual. The preparation of one has been considered but has not been pursued, possibly because AASHTO is writing a general manual on maintenance procedures which they intend to use when it becomes available.

The State is divided into maintenance areas, generally comprising one county (six counties are divided into two areas). Each maintenance area has a foreman in charge, who is responsible for snow and ice control activities. Local weather forecasts are used to anticipate inclement weather. The state highway patrol also alerts the maintenance foremen to hazardous road conditions needing attention.

Plowing and chemical treatment are employed in much the same way as in other states, except that the use of abrasives is confined to occasional application of sawdust or cinders on hills.

No special emphasis is placed on the problem of bridge frosting, and there is not an organized program for bridge patrolling. Apparently, only a few bridges experience frosting with any consistency. One of the most troublesome spots is on I-30 in the southern part of Little Rock where twin bridges about ½ mile long span a river, railroad track, and a highway. Frequent frost occurrence and high accident incidence prompted the highway department to install ice detectors coupled to electrical warning signs. Two Econolite ice-moisture detectors were installed on each bridge, either of which could activate the sign. The system has not operated satisfactorily over its life span of two seasons, and during the 1970-1971 winter the signs were operated manually. (The detectors frequently indicated iciness when none was present and vice versa.) Records were not kept of the performance of the detectors, and no observations were made of driver response when the signs were lighted.

Logs of maintenance activities are not kept by the area foremen. The highway department kept records of frost occurrence and associated maintenance activities on several bridges during the 1970-1971 winter. No frosts were recorded on these bridges during the season.

An annual report is prepared on maintenance costs, broken down only by district and work function. However, maintenance cost records are stored on magnetic tape by work function, county, route, and section. It is, therefore, possible, with a special program, to obtain detailed cost data down to the level of road section. (There may, of course, be several bridges in a section.) Work functions of interest that are available include snow removal, application of chemicals, and application of abrasives.

The computerized cost accounting is relatively new and believed to contain some irregularities. For instance, work function code numbers were changed when the automated system was introduced, and it is suspected that some maintenance activities are incorrectly reported because of confusion between the old and new codes. A pilot area is being set up, one purpose of which is to smooth out the reporting system.

Complete accident data are maintained at the state highway department central office. Accidents are investigated and reports filled out by the state police. The data on each accident are coded on cards by the state police and sent to the highway department where the cards are put on magnetic tape and returned to the state police. The highway department also has microfilm copies of the original accident reports, filed by county, route, and section.

The accident report form includes provision for recording road surface condition (dry, wet, snow, icy, other) and weather conditions (clear, raining, snowing, fog, dust, high wind, other). There is no convenient way to indicate the condition of localized icing, and the general opinion is that the condition would not be reported if it existed.

The coded accident data identify a bridge accident if the abutment or rail is struck. If the accident was precipitated on a bridge but the vehicle(s) did not strike the abutment or rail, the accident would not be coded as a bridge accident. The coded data also include the number of fatalities, the number and severity of injuries, and an estimate of dollar amount of property damage (exclusive of damage to vehicles). An estimate of the vehicle damage is not recorded.

A summary of accident history was provided for the twin bridges on I-30 where the ice detectors are installed. For the period August 1966 to March 1969 there was a total of 48 accidents (as determined from the coded data), 19 of which occurred on a road surface described as icy in the coded data. It is not known if these accidents occurred under localized icing.

CALIFORNIA

California has prepared written maintenance procedures relating to snow and ice control operations. The procedures are general in nature, but provide for the surveillance and treatment of known locally hazardous spots, such as bridge decks, shaded areas, and short radius curves, particularly where marginal freezing temperatures occur. California believes that bridges having a tendency to ice, especially when the approaches may be dry, should be given high priority attention both in patrolling and ice and frost prevention. The procedures recommend that special maintenance patrols should be scheduled on a continuous basis for the detection and correction of slippery conditions on routes where freezing conditions are anticipated. In practice, regular sanding patrols are not maintained on a continuous basis, because the bridge icing is intermittent. Nothing is in the procedures either on the type of abrasives and/or chemicals or on the amounts that are to be used in combating icy bridge conditions. The treatment actually used is determined by the individual area maintenance supervisors and may vary from area to area.

The localized icy bridge problem in California is mainly confined to the central valley area where temperatures seldom fall below 20 F. Bridge icing occurs in the mountainous regions, but the effects are believed to be more critical in the valley areas where the winter climate is less severe and frosting is intermittent. The icy bridge deck problem in the valley areas is usually handled by one of the following procedures (*8*):

1. When there is a high potential for deck icing, a maintenance crew will stand by to apply a salt-sand mixture, if necessary.
2. The highway patrol will inform the local maintenance personnel of any bridges found to be icy.
3. An ice preventive saline solution is periodically sprayed onto the decks. Each application is effective for approximately three days. Some maintenance crews will also make regular applications of salt and sand to bridges in anticipation of bridge icing. This latter procedure is not uniformly followed throughout the valley area. Some crews will sand and salt only after frost or ice has been detected.

The saline solution preventive method, although successful in many ways, has resulted in what is considered premature deterioration of concrete structures. In addition, deicing salts, regardless of the application method, are causing deterioration of decks that have heretofore been maintenance-free. As a result, for the last several years, California has been investigating other ways to combat the problem of bridge deck icing. These investigations include such matters as bridge deck heating, the use of ice detector/warning sign systems, and the development of noncorrosive deicing chemicals, which would be competitive in cost and effectiveness with the chloride type deicers currently in use. The status of their work with various countermeasure systems is discussed in a recent HRB publication (*8*).

Maintenance cost figures associated with the treatment of localized bridge icing are extremely difficult to assemble. Up until July 1970, the cost accounting figures for winter maintenance in California were broken down into the following broad categories: snow and ice control, sanding operations, and removing snow (in the hills).

In July 1970, expanded cost accounting procedures were initiated including a finer breakdown of winter maintenance activities along with estimates of standard man-hours allocated for various tasks. However, neither procedure includes provisions for recording maintenance costs and time spent associated with the treatment of localized bridge icing conditions.

Extremely useful unpublished bridge cost data were obtained from the bridge department during the visit (*9*). Some of the cost data were later published in a report dealing with bridge deck frosting (*10*). The cost data were collected in connection with an in-house study of alternatives that can be used to reduce bridge deck deterioration in new bridges to be located in snow-free salt use areas. The types of cost information obtained were:

1. Frost prevention cost data from three maintenance areas in each of two districts for a 3-year period. The data are broken down by route number and include labor costs, equipment costs, material costs, total costs, and man-hours spent.
2. Sample costs of various alternatives that can be used to reduce bridge deck deterioration. The alternatives include membrane seals, revised slab design, deicing procedures (deicing chemicals with and without abrasives), and bridge deck heating. The sample data include initial, periodic operational or maintenance, and restoration costs. Several bridge deck restoration contract costs and the actual operating costs of several pavement heating installations were obtained.

Data on the frequency of frosting occurrences on selected bridges in several counties were also obtained. Parts of these data were collected to determine if the object crossed by the bridges (such as water, railroads, or roadways) had any influence on the number of frosting occurrences. A small sample of data for various structure types indicated that bridges over water had a higher average frequency of frosting occurrence than bridges over the other objects had.

The other bridge frosting data collected were extracted from a daily diary kept by a foreman in the Yolo County maintenance area. The diary contained entries of the times crews were dispatched for inspection and/or treatment of localized bridge icing conditions in that particular area. Also recorded were any accidents that occurred on the bridges or other roadways within the maintenance area. The headquarters maintenance department does not require foremen to keep a daily diary of maintenance activities. The requirements are left up to the individual district offices and, as a consequence, there is nonuniformity in diary reporting from district to district.

The computerized accident data analyzed by California include entries for bridge accidents under the heading of "Collision with Objects other than Moving Vehicles." The bridge accidents recorded are those involved with the side of a bridge railing and with the end of a bridge with and without guardrails. The computerized accident data do not contain nonfixed-object bridge accidents. To obtain these latter types of data would require a special sorting of the accident files, using the postmile limits of all the bridges.

Provision is made in the data for accidents occurring under frosty or icy pavement conditions. Fixed-object bridge accident data were obtained from the California Division of Highways for 11 selected valley counties. The accident data were supplied in the form of computer listings and cover the years 1964 through 1970. The listings show several accidents occurring under frosty/icy as well as snowy pavement conditions. The accidents recorded under snowy conditions occurred, in all likelihood, under frosty pavement conditions (*11*). The 11 valley counties for which the data apply rarely experience snowfall in the winter time. These bridge accidents were examined for possible use in the benefit analysis, but they were later discarded from further consideration because of the way bridge accident data are coded.

IOWA

Iowa has prepared written maintenance procedures relating to general ice and snow control. The procedures also provide for the treatment of localized frost on bridge decks. These latter guidelines include a "rule-of-thumb" approach to be used by a foreman in forecasting the occurrence of frost on bridge decks within his area of responsibility. The forecasting is based on meteorological data (expected minimum ambient air temperature, wind speed, cloud cover, and current dew point) obtained from the nearest U.S. National Weather Service reporting station. No official record is kept of how often the frost forecasts agree with the actual occurrence of frost.

If the forecast is favorable for frost, a maintenance crewman will report to work early and take either his vehicle or a salting truck and go out looking for frost. Maintenance crews are dispatched also as a result of reports of localized icing conditions received from the highway patrol or all-night service stations. Crews will treat only those bridges found to be frosty and not in anticipation that they will later become locally icy. (Of course, this policy in all likelihood varies from area to area.) The maintenance attitude is that frost is sometimes a very local phenomenon, and one bridge frosting does not mean that others in the same area will be of similar condition.

For the past several years, the Commission has been developing an ice, snow, and frost detection system for use in alerting maintenance foremen of bridge conditions. They believe that this approach towards detection of frost will be more satisfactory than the current hit-and-miss approach.

About one-third, or 45, of the foremen in the State are now keeping a daily record of maintenance activities, including winter snow and ice control. This formal recording was begun in the spring of 1970. Prior to that time, maintenance foremen were not required to keep specific records. Whatever records were kept by foremen were varied in detail and unknown to the central maintenance office. The daily record now filed includes such items as general weather data and a provision for describing the work schedule of each crew (including time spent, job function, and work location). These records are kept at each foreman's location and do not specifically provide for recording when localized icing conditions were treated. This activity and its associated costs are included in the general category of snow and ice control. There is a possibility, although remote, that some foremen might record in their daily record under remarks when frost runs and associated treatments were made. As described earlier in this report, Iowa was one of the states that recorded various data during the 1970-1971 winter on certain maintenance activities associated with treatment of bridges under localized ice and frost conditions. Six occasions of frost were recorded for an Interstate bridge near Iowa City, Iowa (*3*).

Iowa's bridge accident data are considered to be accurate because they contain both fixed-object and nonfixed-object accidents. Care must be exercised in extracting the bridge accidents from the computerized accident files. This is, of course, true for other states' accident files. However, for the Iowa data, the task is made simple, because there is a "bridge" entry listed under the character of roadway in the accident file.

KANSAS

Kansas follows a written procedure in snow and ice control operations. The procedure is general in nature but does provide for the treatment of locally hazardous spots, such as bridges.

About 15 years ago, Kansas experienced what was considered to be an unusually large number of accidents under "frosty" bridge conditions. Since that time, the maintenance department has implemented rather stringent controls on their surveillance and treatment of hazardous road and bridge conditions. When there is a forecast of snow and/or ice, maintenance personnel affected are assigned to 12-hr shifts and equipment is prepared for spreading chemicals and abrasives. Maintenance trucks begin a constant surveillance patrol of their assigned areas with the first snow or ice and falling temperatures. The same vigilance is initiated when conditions are favorable for frost formation on bridge decks. When the forecasts are first received, abrasives are applied at bridges, hills, curves, junctions, and stop signs.

Warning signs, "WATCH FOR ICE ON BRIDGE," are installed each year at all bridges 200 ft in length or longer. Other bridges are signed if requested. These warning signs are put up about mid-November and taken down about mid-April. In this way, an attempt is made to reduce the time a motorist is exposed to the sign when conditions are not favorable for ice formation on the bridge decks.

The maintenance department is of the opinion that both of these countermeasures for treating localized icing conditions (constant surveillance and warning signs) have considerably reduced the winter bridge accidents due to pavement conditions. However, no official study has been conducted.

Maintenance costs and time spent associated with the treatment of localized bridge icing conditions are not readily available. These figures are included in the data recorded under the general heading of "Snow and Ice Control." Snow and ice control data (such as total man-hours equipment usage and tons of abrasives and chemicals used) are available, however, for each of the 27 maintenance districts. These data are used to compare the maintenance performance between districts.

The computerized accident data analyzed by Kansas in-

clude an indirect entry for bridge (or underpass) accidents under the heading of "Special Feature at the Location of the Accident." No provision is made in the data for accidents occurring under localized icing conditions. The fact that a bridge was involved (either directly or indirectly) in the accident must be extracted from a written description of the accident filed by the investigating officer. Bridge, per se, is not included in the list of road characteristics appearing on the accident report.

All fatality accidents occurring in Kansas are reviewed in detail, and, in some instances, the location of the accident is personally inspected for possible causes. It is possible that fatal bridge accidents under localized icing conditions might be found from these detailed fatality studies. These studies, however, will not provide clues as to the number of less severe accidents occurring under localized icing conditions.

In 1974, the Research Division completed a 2½-year HPR-funded study (*12*) to determine: (1) the frequency of bridge deck frosting on 14 structures in the state; (2) the number and seriousness of accidents resulting from a frosted bridge deck; (3) the factors responsible for creating frosting conditions; and (4) a method of predicting in advance the probability of frost occurrence on a bridge deck. Although some data were reported on the frequency of frost occurrence, they were insufficient to determine frosting frequency or to assist in determining accident frequency resulting from frosting conditions. The data collected also did not provide a way to predict when frost might occur on a given bridge deck.

MICHIGAN

Michigan provides direct maintenance for only about one-fourth of the counties (21 out of 83 counties) in the State. Maintenance of the remaining counties is performed by private concerns under contract arrangements. The contracted maintenance forces generally follow the same guidelines and keep about the same records as do the state maintenance personnel, even though they are not required to do so. Consequently, the following description of winter maintenance operations in Michigan pertains mainly to those counties under direct state control.

Michigan does not have a formal written operating procedure relating to general ice and snow control. The maintenance department distributes a Winter Operations Guide and instructions on filing various winter maintenance reports. The Guide is a tabulation of recommended sanding, salting, and plowing procedures during and after storms as a function of temperature conditions. No specific reference is made to treating frosty or locally icy bridge decks, although these conditions are well recognized by the State as hazardous situations.

The detection of localized icy and frosty bridge deck conditions (on the major routes) is accomplished by a roving night patrolman. A night patrolman, working between 10 PM and 6 AM, is used by each garage from about the first of November until the first of April. In addition to watching for frost conditions, the patrolman keeps watch on approaching storms and performs other maintenance tasks. The responsibility of each patrolman is approximately 20 lane-miles, and he might make as many as three round trips in one 8-hr period. He will treat, with sodium chloride, those bridges that have become icy and, in general, will not salt bridges in anticipation that they will become icy or frost covered.

At the end of his shift, a patrolman will fill out a Night Patrolman's log describing significant events that occurred during the road patrols and work functions performed. Times and locations are also included in the description. The log sheets have been in use for the past several years and are filed in the respective maintenance garages. It is possible that the log sheets contain data on the inspection for, and treatment of, bridge icing. However, this information is not specifically requested in the written instructions, and the consistency of reporting might vary from garage to garage.

An Operations Winter Report is completed every time a maintenance person works on the major winter activity of snow and ice control that includes plowing, blading, salting, or sanding. This report is the primary source of data on winter operations for the work reporting system. The Operations Winter Report provides specific information on salt and sand applications, including amounts used and rate of application. These reports are kept at each garage location for 1 year. Summaries of these reports are sent at regular intervals from the foreman level to the next higher level of supervision. After each storm a Salting Rate Summary is filled out and sent to the next level of supervision. This latter report summarizes the salt application rate that each operator, foreman, and area/county superintendent has used.

Maintenance cost figures associated with the treatment of localized bridge icing are not readily available. These costs are included in the data recorded under the general heading of "Snow and Ice Control." Snow and ice control data (such as total costs and tons of salt used) are available, however, for each county on a per "E" mile basis. (An "E" mile is defined as a 24-ft wide pavement, 1 mile long.)

The computerized accident data analyzed by Michigan include an entry for bridge accidents under the heading of "Objects Hit in the Accident: Bridge Pier or Abutment and Bridge Rail or Deck." There is some reason to question the use of the recorded data in this research. First, the bridge accidents of interest in this study should not include those accidents involving the bridge piers. It would be difficult to remove those bridge pier accidents from the set of fixed-object accidents without reviewing the original accident reporting form. Second, the fixed-object bridge accident data do not include those accidents in which the bridge was not physically struck but was a contributing factor in the accident.

The computerized accident data include, however, a provision for accidents occurring under localized icy or frosty bridge deck conditions. These frosty bridge accidents are listed under "Road Defect," and their classification does not require the bridge to be directly hit. The frosty bridge accident data are classified by encoders from the written description given in the original accident report. The MDSH is suspicious of the total number of frosty bridge accidents recorded and believes that there are probably more which are unreported as such.

MISSOURI

Missouri follows a written procedure in snow and ice control operations. The recommended procedures are general in nature. They are intended for use as a guide in determining the amounts and type of chemicals, abrasives, or mixtures to be applied for various pavement conditions. The procedure provides for the treatment of locally hazardous spots, but no direct reference is made to the treatment of bridges. However, the maintenance personnel are to patrol the roadway after a storm until the pavement is clear. Special care is recommended when plowing newly sealed roadway surfaces and bridge decks. The snow plow blades are to be raised slightly when plowing these surfaces to prevent damage to the seal. Bridges in urban areas where chemical usage is high are to be swept and flushed (weather permitting) after storms to remove accumulations of abrasives and deicing chemicals.

Nothing is specified in the procedures about the treatment of frosty bridge decks. However, local maintenance personnel are aware of the potential hazards of such situations. During periods of potential bridge frosting, a designated maintenance person will come to work several hours early and specifically look for frosty or localized icy bridge deck conditions. He will first inspect "indicator" bridges, or bridges that have been observed in the past to ice up before others. Crews are dispatched on reports of localized icing conditions received from him or from the highway patrol. In general, crews are to treat only those bridges found to be frosty and not in anticipation that they will later become icy.

In the past, maintenance foremen were required to keep a daily diary of maintenance activities. It is possible that some of the foremen might have recorded times of inspection and treatment of locally icy bridge decks, even though this type of information was not specifically requested. The maintenance foremen are no longer required to keep daily diaries. This type of record keeping stopped several years ago.

Maintenance costs and time spent associated with the treatment of localized bridge icing conditions are not readily available. These figures are included in the data recorded under the general heading "Snow and Ice Control." Snow and ice control cost data (such as total labor, equipment usage, chemicals, and abrasives used) are available only for each maintenance district. Missouri at one time tried to break the cost down by county and route number but abandoned this approach.

The Missouri computerized accident data include an indirect entry for bridge accidents under the heading of "Bridge Width." The actual width of the bridge is coded for those accidents in which a bridge was struck. A blank entry means that the data are not given or that a bridge was not struck. The associated accident report filed contains the bridge number of the structure hit. No provision is made in the data or report for accidents occurring under localized icing conditions. However, in some instances, the presence of frost or localized ice on the bridge deck is noted in the written description filed by the investigating officer. The recording of this latter information probably varies from officer to officer.

OHIO

Ohio has prepared written maintenance procedures for treating general ice and snow conditions and locally hazardous spots, such as icy bridges and overpasses. The procedures are of a general nature and serve as basic guidelines only. The maintenance department recognizes that the localized icing problem, let alone the general snow and ice treatment, can not be determined by a set formula. According to department procedures: "The variables of location, temperature, precipitation and traffic, make snow and ice control treatments an inexact science. Successful implementation of snow and ice control operations depends greatly upon the experience and judgment of the superintendents and the men on the road."

The detection of localized ice and frost bridge deck conditions is accomplished by roving night maintenance patrols and also from reports by the state highway patrol. Maintenance patrols are not dispatched on a regular schedule. Instead, county superintendents will send the maintenance patrol out (in either a pickup or truck with salt) when they consider conditions favorable for localized icing or when a storm is approaching. The patrol will treat those bridges that have become icy but, in general, will not salt bridges in anticipation that they will become icy or frost covered. The responsibility of each maintenance patrol is approximately 20 to 30 lane miles.

A Road Condition and Operation Report is filled out at the county garage by a timekeeper from reports received from night patrols and road crews. This form lists various meteorological and road conditions in addition to defining the type of ice and snow control function performed (plowing, sanding, salting, etc.) and the amounts of materials used. These reports are kept on file at the various county garages for summarization on request by the division offices. County road conditions are summarized and sent to the division offices, which, in turn, again summarize the information for transmission to the central maintenance office. Road conditions summary reports are filed twice a day during the winter months.

Individual icy bridges are not singled out in the summary reports. These situations might be listed only as "a few icy spots." If any data exist on icy or frosty bridges, they would be available only from the reports filled out by the county night patrols. These data would appear only indirectly under remarks made, since the forms do not provide for special treatment of bridges.

Maintenance cost figures associated with the treatment of localized bridge icing are virtually nonexistent. Ohio's cost accounting figures for winter maintenance are broken down into the following broad categories:

- Snow and ice control.
- Plowing snow and applying chemicals, abrasives, and mixtures.
- Erecting, repairing, and removing snow fences.
- Cleaning bridges, catch basins, and inlets (incidental to snow and ice).

The account for snow and ice control is a catch-all category and is not further delineated.

Ohio has developed regression models for predicting an-

nual snow removal costs and chemical usage per lane mile of various types of roadways. Some of their preliminary findings have been published (*13*), and they are currently working on improved models that include their most recent data and account for more variables than the original models. These models are used both to budget winter maintenance costs for future winters and also as a "method" to measure and compare past maintenance work performances. The models provide insight into the influence of various parameters (ADT, snowfall amount, etc.) on maintenance costs and might be applicable indirectly to the problem of bridge icing, even though bridge maintenance is not explicitly included in the models.

Ohio's Bureau of Traffic is quite concerned about the number of bridge accidents that occur each year within the State. (Ohio has approximately 12,500 to 13,000 bridges on 38,794 lane miles of roadway under maintenance control.) Approximately 55 to 60 percent of all bridge accidents recorded occur during the five winter months (November through March). About half of the bridge accidents in the last two winters have occurred under icy or snowy pavement conditions.

The bridge accident data analyzed by Ohio are obtained from computer programs that compare accident records with a road inventory. An accident is classified as a bridge accident if it occurs on the bridge. (Ohio believes that an interesting analysis of bridge accidents could be performed by investigating all accidents that occur both on the bridge proper and within a short road segment on either end of the bridge; bridge accidents determined in this fashion should reflect the proper influence of the bridge on the accident.) Bridges are defined by milepost markers. Unfortunately, the computer printout of the accident data neither isolates those accidents occurring under localized icy or frosty bridge conditions, nor does it distinguish between an icy or snowy road condition.

Several studies have been performed by the Bureau of Traffic in an attempt to find means of reducing the number of icy bridge accidents. In a recent study (*14*) the effectiveness of "WATCH FOR ICE ON BRIDGE" signs was evaluated. Accident rates on 24 pairs of "test" and "control" bridges were compared for 3-year periods before and after use of the signs was begun on the test bridges. The signs were used only during the winter months. Analysis of the data showed a statistically significant reduction in the number of icy or snowy bridge accidents attributable to the signs.

The Bureau of Traffic is currently conducting an in-house study of bridge accidents from the past 2 years, particularly the ones that have occurred under icy or snowy pavement conditions. They are reviewing the actual accident reports filed and are gathering data on the characteristics of all bridges involved. The goal is to develop a bridge classification model (similar to the one presented in this report) in an attempt to isolate major factors influencing bridge accidents under icy or snowy conditions.

PENNSYLVANIA

Pennsylvania has a written manual on maintenance procedures for snow removal and ice control. The procedures are aimed primarily at keeping the roads clear during snow storms. No emphasis is placed on bridges, except the manual directs that, at the beginning of a storm, abrasives should be applied to predesignated locations that become hazardous immediately; namely, bridge decks, steep grades, etc.

Through contract with Northeast Weather Services, warnings of impending inclement weather are telephoned directly to district offices. The forecast is given by county, and the information is relayed by the district office. On the basis of the storm-warning information, the county maintenance superintendent determines what types of operation will be required. During the course of a snow storm and the subsequent cleanup, each district submits weather and road condition reports twice daily (during daytime hours). Road conditions are given by county and route. It would be possible to obtain a rough estimate of the frequency of occurrence of various road conditions from these reports, but bridges could not be pinpointed.

The problems of bridge frosting and localized icing are not covered in the maintenance manual. It is the opinion of the maintenance engineer that some frost patrolling and bridge treatment may be conducted on a local (county) level based on experience. Each maintenance foreman keeps a diary of the activities of his crews. Although details probably vary from foreman to foreman, the diaries are a possible source of information on maintenance activities associated with localized bridge icing. The maintenance engineer agreed to have some of the foremen record such activities (if any) during the current winter season. Some occasions of frost were reported; however, most of the problems with localized icing appear to occur during storms.

An annual report is issued on winter maintenance costs. Included are costs for the purchase and hauling of abrasives to stockpile; purchase of chemicals; application of abrasives and chemicals; snow and ice removal; and purchasing, erection, and dismantling of snow fences. The costs are broken down by county, however, and are not sufficiently detailed to indicate the cost of winter maintenance activities for bridges. Bridge deck repair costs are also not independently summarized in the annual over-all maintenance cost report.

Accident data are available for the approximately 44,000 miles of roadway under the jurisdiction of the department. About 300,000 accidents are reported each year. Data from the accident report forms are coded, stored on magnetic tape, and retained for 3 years. The data include a code for accidents occurring on bridges and an indication of pavement condition. One could, therefore, pick out the icy bridge accidents from a listing of all accidents, or write a special program to obtain a listing of the icy bridge accidents by themselves. The case of localized icing is not identified on the tape, however, and the general opinion is that the condition would not be noted in the original accident reports. (The original reports are kept for 4 years and can be made available on request.) Other data on the tape include location in the state, date, type of accident (rear-end, side-swipe, etc.), number killed, number injured (the original accident report identifies three levels of injury severity, but this breakdown is not carried over to the magnetic tape), an estimate of dollar amount of property dam-

age, description of vehicle movements, and hypothesized cause of accident.

An interesting statistical summary of accidents is prepared annually. This summary gives, among other details, the number of fatal, injury, and property damage accidents on bridges and (separately) the number on icy roadways.

VIRGINIA

Virginia has a written manual on maintenance procedures for snow and ice control. Special reference to the problem of bridge icing is included. It is emphasized that serious accident-prone situations (localized icing) are likely to occur because the bridges are the first to freeze and the last to be completely cleared of snow or ice. When weather conditions are conducive to bridge icing, the bridges are patrolled and abrasives treated with calcium chloride are applied at the first sign of icing. (At low temperatures straight calcium chloride is used.) It is not general policy to treat bridges in anticipation of ice or frost. Patrol of the bridges is maintained until the deck is free of ice.

The majority of bridge icing problems in Virginia arise as the result of some form of precipitation. Through contract with Northeast Weather Services, warnings of impending inclement weather are telephoned directly to the district offices. The information is disseminated to the maintenance areas within the districts and, on the basis of this information, the area superintendents decide when to initiate maintenance procedures.

No special emphasis is placed on the bridge frosting problem, and no reference is made to this condition in the maintenance manual. Frosty bridegs may be reported by the highway patrol and subsequently treated. Some maintenance area superintendents may on occasion dispatch bridge patrols based on experience.

At the present time five Econolite detection devices (plus an Icelert) along with their respective warning systems have been installed in the field, and others may be installed if problems with the detector and also with obtaining the required FCC license for transmission are resolved.

During periods when inclement weather necessitates snow and ice control maintenance activities, road condition reports are submitted three times daily (during daytime hours) by each district to the central office in Richmond. Road conditions are given by county and route. The records are kept on file and could be used (with effort) to estimate the frequency of occurrence of various road conditions. Bridges could not be pinpointed, however, because the reported conditions are averages taken over relatively long stretches of road.

Records are not kept which identify maintenance activities for bridges alone. Annual material (calcium chloride, sodium chloride, and abrasives) costs are summarized by route and section. Manpower costs per section could be obtained from daily crew time sheets filed by maintenance foremen. Each section may, however, include a number of bridges.

Accident statistics are available for the 50,000 miles of roadway under the jurisdiction of the Virginia Department of Highways (approximately 8,000 miles of Interstate and primary, and 42,000 miles of secondary routes). About 135,000 accidents are reported yearly, 75 to 80 percent of which are investigated by police. The state accident report form includes an indication of surface condition (dry, wet, snowy, icy, muddy, oily) and weather (clear, cloudy, fog, mist, raining, snowing, sleeting, smoke-dust). There is no provision for recording localized icing except possibly under accident description. The general opinion is that the condition would not be recorded, even if it existed. (Each fatal accident is investigated by a highway engineer and a special report prepared; the possibility of localized icing being reported may be somewhat better in these cases.)

The reported accidents are coded on IBM cards to facilitate analysis. A unique code for bridge accidents is not included; i.e., the cards can not conveniently be sorted to extract bridge accidents. (Bridges are classified in the general category of structures that include underpasses, culverts, etc.). To isolate bridge accidents, it would be necessary to refer to the Graphic Log * or section maps to determine route, section, and milepost for each bridge and sort accordingly.

The coded data include an estimate of the dollar amount of property damage. Accidents are classified as fatal, nonfatal, and property damage only. There is no gradation on severity of injury. (The injury severity is described in the original accident report.)

A comprehensive summary of accident statistics is published annually.

* A Graphic Log is maintained for the Interstate and primary systems. It shows roadway characteristics in detail and local landmarks (places of business, etc.), and is used primarily to help pinpoint high-accident rate locations.

APPENDIX B

BENEFIT MODEL

The general benefit model is described in Chapter Two. In this appendix, an expansion of that model is presented to illustrate how the model should be interpreted and applied. The results of the model expansion are individualized

benefit models for each feasible countermeasure or practical combination of countermeasures.

The model expansion contains five possible road surface conditions. This number can be raised or lowered to fit specific needs and available data. Once the model formulation is understood, such desired modifications should be easy to perform.

The benefit model is used to calculate the dollar value of accidents reduced by a countermeasure system for *localized* ice and frost. The annual benefit is defined as the difference between accident costs per year without special countermeasures and accident costs per year with special countermeasures.

The general benefit model for localized bridge icing countermeasure systems is written compactly as follows:

$$B = \sum_{m=1}^{5} T_m R_m K_m - \sum_{m=1}^{5} T_m \left[\sum_{n=1}^{5} P_{mn} (1 - A_n) R_n K_n \right]$$

or

$$B = \sum_{m=1}^{5} T_m \left[R_m K_m - \sum_{n=1}^{5} P_{mn} (1 - A_n) R_n K_n \right] \quad \text{(B-1)}$$

where:

B = annual dollar benefits of accident reduction resulting from application of the localized countermeasure system;

m, n = indexing numbers for bridge surface conditions that relate to vehicular traction, as follows:
- 1 = dry
- 2 = wet
- 3 = abrasives on ice
- 4 = localized ice or frost on bridge deck only
- 5 = generalized ice, frost, or snow

T_m = time, in hours per year, when a bridge surface is condition m without any localized countermeasures;

R_m, R_n = accident rate per hour of surface condition m or n;

K_m, K_n = average dollar cost per accident that occurs for surface condition m or n;

P_{mn} = proportion of time, T_m, converted to surface condition, n, by the localized countermeasure system; the condition $m = n$ describes the proportion of time, T_m, that the countermeasure system fails to change the surface condition; for any surface condition, m, the sum of the P_{mn}'s, $\sum_{n=1}^{5} P_{mn}$, must equal unity; and

A_n = proportion of accidents reduced for surface condition n by a localized countermeasure system (e.g., signing) that does not change the surface condition.

EXPANSION OF THE MODEL

A full expansion of the model is academic because many terms are either zero or unity for the state of the art in localized countermeasure application. Therefore, before the expanded form is presented, the feasible countermeasures and their practical combinations, and the model terms that are either zero or unity, will be discussed.

The feasible localized countermeasures and their practical combinations include:

1. Local Countermeasures—heating, signing, deicers, abrasives, and sand/salt mix.
2. Combinations of Local Countermeasures—signing and abrasives, signing and deicers, and signing and sand/salt mix.

By considering only the feasible localized countermeasures and their combinations, many of the P_{mn} and A_n terms can be eliminated, and the general model can be written in a more easily understood explicit form. The following considers the pertinence of the terms.

1. Elimination of P_{mn} Terms—
   a. P_{54} is zero because a localized countermeasure can not change a generalized ice, frost, or snow surface condition to a localized ice or frost surface condition.
   b. P_{45}, P_{35}, P_{25}, and P_{15} are all zero because localized countermeasures can not change localized surface conditions to generalized ice, frost, or snow surface condition.
   c. P_{34} is zero because none of the localized countermeasures removes the abrasives and nothing else.
   d. P_{24} and P_{23} are zero because none of the localized countermeasures freezes standing water.
2. Elimination of A_n Terms—The only localized countermeasure considered that does not change the surface condition is signing. Signing is assumed effective only when ice, frost, or snow, either with or without abrasives, is present on the bridge. In addition, warning signs could have potential benefits for both localized and generalized surface conditions. Therefore, A_2 and A_1 are zero.

By eliminating all of these zero terms, the expanded general model is as follows:

$$\begin{aligned} B = {} & T_5 [R_5 K_5 - P_{55}(1 - A_5) R_5 K_5 - P_{53}(1 - A_3) R_3 K_3 \\ & \quad - P_{52} R_2 K_2 - P_{51} R_1 K_1] \\ & + T_4 [R_4 K_4 - P_{44}(1 - A_4) R_4 K_4 \\ & \quad - P_{43}(1 - A_3) R_3 K_3 - P_{42} R_2 K_2 - P_{41} R_1 K_1] \\ & + T_3 [R_3 K_3 - P_{33}(1 - A_3) R_3 K_3 - P_{32} R_2 K_2 \\ & \quad - P_{31} R_1 K_1] \\ & + T_2 [R_2 K_2 - P_{22} R_2 K_2 - P_{21} R_1 K_1] \\ & + T_1 [R_1 K_1 - P_{14}(1 - A_4) R_4 K_4 \\ & \quad - P_{13}(1 - A_3) R_3 K_3 - P_{12} R_2 K_2 \\ & \quad - P_{11} R_1 K_1] \end{aligned} \quad \text{(B-2)}$$

APPLICATION OF EXPANDED MODEL TO SPECIFIC COUNTERMEASURE SYSTEMS

The expanded benefit model serves as a basis for deriving specific benefit submodels for each localized countermeasure or combination of countermeasures. Before presenting the submodels, it is instructive to discuss each line of the expanded general model remembering that the T_m terms are the number of hours per year that surface condition m exists without localized countermeasures. The values of the T_m terms are, however, contingent on the surface condition

changes effected by generalized countermeasures.

The *first* line of the model accounts for benefits from localized countermeasures that also have benefits during generalized surface conditions. The *second* line of the model accounts for benefits from all localized countermeasures during localized surface conditions. The *third* line accounts for benefits from localized countermeasures when the general surface condition is "abrasives on ice" due to a generalized countermeasure. If generalized abrasives are not used, this line is deleted from the specific benefit submodel. The *fourth* line accounts for benefits from automatic bridge heating when the general surface condition is wet. When the weather is cold and wet, the heating system could be activated to dry the bridge surface. The *fifth* line accounts for negative benefits from localized deicers when they remain after the surface becomes dry. Chloride deicers can attract moisture from the air, which could freeze with dropping temperatures.

The benefit submodels for each localized countermeasure or combination of countermeasures are as follows:

1. Bridge Heating (B_H)—

$$\begin{aligned} B_H = {} & T_5(R_5 K_5 - P_{55} R_5 K_5 - P_{52} R_2 K_2 - P_{51} R_1 K_1) \\ & + T_4(R_4 K_4 - P_{44} R_4 K_4 - P_{42} R_2 K_2 - P_{41} R_1 K_1) \\ & + T_3(R_3 K_3 - P_{33} R_3 K_3 - P_{32} R_2 K_2 - P_{31} R_1 K_1) \\ & + T_2(R_2 K_2 - P_{22} R_2 K_2 - P_{21} R_1 K_1) \end{aligned} \quad \text{(B-3)}$$

2. Bridge Warning Signs (B_s)—

$$\begin{aligned} B_s = {} & T_5 [R_5 K_5 - (1 - A_5) R_5 K_5] \\ & + T_4 [R_4 K_4 - (1 - A_4) R_4 K_4] \\ & + T_3 [R_3 K_3 - (1 - A_3) R_3 K_3] \end{aligned} \quad \text{(B-5)}$$

or

$$B_s = T_5 A_5 R_5 K_5 + T_4 A_4 R_4 K_4 + T_3 A_3 K_3 \quad \text{(B-4)}$$

3. Localized Deicers on Bridge (B_D)—

$$\begin{aligned} B_D = {} & T_5(R_5 K_5 - P_{55} R_5 K_5 - P_{52} R_2 K_2 - P_{51} R_1 K_1) \\ & + T_4(R_4 K_4 - P_{44} R_4 K_4 - P_{42} R_2 K_2 - P_{41} R_1 K_1) \\ & + T_3(R_3 K_3 - P_{33} R_3 K_3 - P_{32} R_2 K_2 - P_{31} R_1 K_1) \\ & + T_1(R_1 K_1 - P_{14} R_4 K_4 - P_{12} R_2 K_2 - P_{11} R_1 K_1) \end{aligned}$$

4. Localized Abrasives on Bridge (B_A)—

$$\begin{aligned} B_A = {} & T_5(R_5 K_5 - P_{55} R_5 K_5 - P_{53} R_3 K_3) \\ & + T_4(R_4 K_4 - P_{44} R_4 K_4 - P_{43} R_3 K_3) \end{aligned} \quad \text{(B-6)}$$

5. Localized Sand/Salt Mix on Bridge (B_{SS})—

$$\begin{aligned} B_{SS} = {} & T_5(R_5 K_5 - P_{55} R_5 K_5 - R_{53} R_3 K_3 - P_{52} R_2 K_2 \\ & - P_{51} R_1 K_1) \\ & + T_4(R_4 K_4 - P_{44} R_4 K_4 - P_{43} R_3 K_3 - P_{42} R_2 K_2 \\ & - P_{41} R_1 K_1) \\ & + T_3(R_3 K_3 - P_{33} R_3 K_3 - P_{32} R_2 K_2 - P_{31} R_1 K_1) \\ & + T_1(R_1 K_1 - P_{13} R_3 K_3 - P_{12} R_2 K_2 - P_{11} R_1 K_1) \end{aligned} \quad \text{(B-7)}$$

6. Localized Signing and Abrasives on Bridge (B_{SA})—

$$\begin{aligned} B_{SA} = {} & T_5 [R_5 K_5 - P_{55}(1 - A_5) R_5 K_5 \\ & - P_{53}(1 - A_3) R_3 K_3] \\ & + T_4 [R_4 K_4 - P_{44}(1 - A_4) R_4 K_4 \\ & - P_{43}(1 - A_3) R_3 K_3] \\ & + T_3 A_3 R_3 K_3 \end{aligned} \quad \text{(B-8)}$$

7. Localized Signing and Deicers on Bridge (B_{SD})—

$$\begin{aligned} B_{SD} = {} & T_5 [R_5 K_5 - P_{55}(1 - A_5) R_5 K_5 \\ & - P_{52} R_2 K_2 - P_{51} R_1 K_1] \\ & + T_4 [R_4 K_4 - P_{44}(1 - A_4) R_4 K_4 \\ & - P_{42} R_2 K_2 - P_{41} R_1 K_1] \\ & + T_3 [R_3 K_3 - P_{33}(1 - A_3) R_3 K_3 \\ & - P_{32} R_2 K_2 - P_{31} R_1 K_1] \\ & + T_1 [R_1 K_1 - P_{14}(1 - A_4) R_4 K_4 \\ & - P_{12} R_2 K_2 - P_{11} R_1 K_1] \end{aligned} \quad \text{(B-9)}$$

8. Localized Signing and Sand/Salt Mix on Bridge (B_{SSS})—

$$\begin{aligned} B_{SSS} = {} & T_5 [R_5 K_5 - P_{55}(1 - A_5) R_5 K_5 \\ & - P_{53}(1 - A_3) R_3 K_3 - P_{52} R_2 K_2 \\ & - P_{51} R_1 K_1] \\ & + T_4 [R_4 K_4 - P_{44}(1 - A_4) R_4 K_4 \\ & - P_{43}(1 - A_3) R_3 K_3 - P_{42} R_2 K_2 \\ & - P_{41} R_1 K_1] \\ & + T_3 [R_3 K_3 - P_{33}(1 - A_3) R_3 K_3 \\ & - P_{32} R_2 K_2 - P_{31} R_1 K_1] \\ & + T_1 [R_1 K_1 - P_{13}(1 - A_3) R_3 K_3 \\ & - P_{12} R_2 K_2 - P_{11} R_1 K_1] \end{aligned} \quad \text{(B-10)}$$

APPENDIX C

ACCIDENT ANALYSIS

INTRODUCTION

The implementation of the benefit model to the bridge icing problem requires knowledge of several parameters. Among the quantities needed are bridge accident rates as a function of various pavement conditions. These rates are determined from bridge accident data and an estimate of road surface exposure times (see Appendix E). This appendix briefly describes the bridge accident data collected during the course of the study and the data finally selected for quantifying accident rates. Bridge accident rates for the five types of road surface conditions (generalized ice or snow, localized ice or snow, abrasives on ice, wet and dry) are then presented for selected regions of the country. These rates are used, subsequently, in the illustrative examples of the cost-benefit methodology described in Appendix H. The rate data are followed by a discussion of the relationship between accident rates and exposure times. Finally, the annual number of bridge accidents under localized icing conditions are estimated.

BRIDGE ACCIDENT DATA

Requests for computerized bridge accident data were made of several of the state highway departments visited and from other sources. The states and location where bridge accident data were obtained are given as follows:

1. California (11 valley counties for 1964-1970; the 11 counties for which the data apply very seldom experience snowfall in the winter).
2. Iowa (1966-1969).
3. Michigan (1968-1969, and several years of data for the Flint River Bridge).
4. Ohio (April 1968 through March 1970).
5. Virginia (one pair of bridges on I-95 for the years 1965-1968).
6. Texas (1968-1969).
7. Denver, Colo., area (1969).

The California, Iowa (1966-1968), Michigan (except 1969), and Virginia bridge accident data were obtained from a study of ice and snow detection and warning systems (*3*). The Texas data were borrowed from the Texas Transportation Institute, which collected the data for use in their study of bridge rail service requirements (*15*). The Denver data were obtained from the Highway Safety Research Institute's data file. Accompanying the Denver bridge accident data were the results of a simplified analysis showing the interaction of the accidents (as a function of pavement condition) with other recorded data.

Investigations were made of the bridge accident data gathered to determine the completeness and/or validity of the data. Some of the results of the investigations were referenced previously in the discussions of the states visited (see Appendix A). The outcome of these studies resulted in the isolation of those sets of bridge accident data considered most reliable for use in quantifying the accident rates. The bridge accident data selected for further use are from the following states and specific location: Iowa (1966-1969), Ohio (April 1968 through March 1970), Texas (1968-1969), and Virginia (one pair of bridges on I-95 for the years 1965-1968).

These states and location represent a sampling of the hazardous winter conditions that exist throughout the United States. The resulting accident data therefore reflect not only the different climatic conditions, but also the winter maintenance practices that exist in various areas. The extremes in climatic conditions range from areas in Texas that experience a yearly average snowfall of about 1 in. to the northeastern corner of Ohio with over 50 in. of snow annually.

The remainder of the bridge accident data collected was not used in the study, mainly because the data lacked completeness. The data reported, in general, reflected only fixed-object bridge accidents and did not include those accidents in which the bridge was not physically struck but was a contributing factor in the accident. Both fixed-object and nonfixed-object bridge accidents need to be included in the estimation of bridge accident rates. In the case of Iowa's bridge accident data, the nonfixed-object data amounted to about 36 to 55 percent of the total bridge accident data for the 2 years considered. The 2 years of Iowa's data rejected were sorted (by computer) in a different manner from the 1966-1969 data, and did not include the nonfixed-object bridge accidents. The Michigan Flint River data were discarded because of incompleteness and sample size. Accident severity was not available for all the accidents recorded. In addition, a motorist's warning sign was installed during the course of the period, which undoubtedly had an influence on the accident rate. The presence of the safety countermeasure divided the data into two groups, thus effectively reducing the data sample size available. The Denver data were rejected because, unfortunately, it was impossible to extract from the data the exact number of property-damage-only (PDO) accidents and also the involvement of the bridges in the accidents, without spending a disproportionate amount of time collecting the missing information.

The bridge accident data from the four areas (Iowa, Ohio, Texas, and Virginia) were manually sorted by pavement conditions existing at the time of the accident; i.e., icy, snowy, wet, and dry. The accidents under icy and snow conditions were later combined. The separate category of icy bridge accidents was retained, where possible, for use in an attempt to isolate those accidents that could have resulted from localized bridge icing conditions. (More will be said about this attempt later in this appendix.) The accident data were then subdivided into fatal, injury, and PDO accidents.

Each of the three states for which statewide accident data were available (i.e., Iowa, Ohio, and Texas) was divided into five meteorological regions by considering the distribution of the average annual snowfall within each state and also the locations of the major weather reporting stations. One reporting station was chosen for each region as being representative of the weather experienced within that region. The closest major weather reporting station to the bridge location in Virginia was selected. All of the reporting stations are located at airports.

Estimates of the number of hours per year of ice or snow, wet, and dry pavement conditions prevailing during the years of the accident data were determined for each of the meteorological regions mentioned previously. The hours of ice or snow were subsequently divided into generalized ice or snow and localized ice or snow. The road exposure values were computed from detailed local climatological data collected for the respective reporting stations, using the procedure outlined in Appendix E. Each of the bridge accidents assembled from the four areas was then assigned to a specific meteorological region.

The data (the bridge accidents and their associated exposure times) assembled for each of the four areas are presented as follows.

Iowa

The Iowa statewide bridge accident data were supplied by the Iowa State Highway Commission in the form of computer listings. The listings contained all bridge accidents occurring on the Interstate and primary systems. The 1966 data contain only rural accidents, whereas the 1969 data contain both urban and rural accidents.

The five weather reporting stations selected were located in the following cities:

Region 1—Sioux City, Iowa.
Region 2—Waterloo, Iowa.
Region 3—Omaha, Nebraska (across the Missouri River from Council Bluffs, Iowa).
Region 4—Des Moines, Iowa.
Region 5—Moline, Illinois (across the Mississippi River from Davenport, Iowa).

Estimates of the fraction of time that the various bridge conditions prevailed during each of the 2 years are given in Table C-1 for each region.

A tabulation of the number of fatal, injury, and PDO accidents by regions and road conditions is given in Table C-2 for both the Interstate and primary highway systems. Likewise, Interstate accident data for 1969 are given in Table C-3. Of the four sources of data considered only the Iowa computerized accident data contain a breakdown by type of injury (a, b, and c classification). These types of injury accidents are not distinguished in the last two tables in order to present data consistent with the other accident data. In addition, some of the classification data were missing from the computerized data.

One interesting observation of the data is that no fatal accidents were recorded in 1969 on the Interstate bridges under ice or snow conditions. This is also true for the 1966 Interstate data. The one fatal crash recorded in 1966 under icy pavement conditions occurred on the primary system and resulted in three fatalities; the one fatal crash (resulting in one fatality) recorded in 1969 occurred under a snowy pavement condition.

Ohio

The Ohio statewide bridge accident data were supplied by the Bureau of Traffic, Ohio Department of Highways, in the form of computer listings. The data contained all bridge accidents occurring on the Interstate, primary, and secondary systems (both rural and urban) for two consecutive years (April 1968 through March 1970). The bridge accident data inadvertently contained some ramp accidents that were extracted from the listings by manually sorting the data. No distinction is made in the data for accidents occurring under icy and snowy pavement conditions—accidents in these two categories are combined.

Weather data were obtained from reporting stations in the following five cities:

Region 1—Cleveland, Ohio.
Region 2—Mansfield, Ohio.
Region 3—Youngstown, Ohio.
Region 4—Columbus, Ohio.
Region 5—Huntington, W. Va. (near the extreme southern limit of Ohio).

Estimates of the fraction of time that the various bridge conditions prevailed during the 2 years are given in Table C-4 for each region. Region 1 normally experiences an average annual snowfall of 50 in. or more. Region 3 also experiences a high average annual snowfall (in the range 40 to 70 in.). The effects of these large amounts of frozen precipitation are reflected in the number of hours of ice or snow for Regions 1 and 3. Region 5 normally experiences snowfall amounts of 20 in. or less.

A tabulation of the number of fatal, injury, and PDO accidents by region and road condition is given in Table C-5. The four fatal crashes in 1968-1969, and the two in 1969-1970, recorded under ice or snow pavement conditions occurred on the primary and secondary systems.

Texas

The Texas statewide bridge accident data for the period 1968-1969 were borrowed from the Texas Transportation Institute, which, in turn, had originally obtained the information from the Texas Highway Department. The accident data were contained on computer printout sheets in an uncoded format. The data included all accidents that occurred in the immediate vicinity of bridge structures located on all types of rural highways in Texas.

Weather data were obtained for five meteorological regions represented by the following cities:

Region 1—Amarillo, Texas.
Region 2—Lubbock, Texas.
Region 3—Wichita Falls, Texas.
Region 4—Waco, Texas.
Region 5—Austin, Texas.

Region 5 has an average annual snowfall amount of 1 in. or less; Region 4, between 1 and 4 in.; Region 3, between 4 and 6 in.; Region 2, between 6 and 12 in.; and Region 1, 12 in. or more. Regions 1 and 2 comprise the panhandle area of Texas.

Estimates of the fraction of time that the various bridge conditions prevailed in Texas during the 2 years are given in Table C-6 for each region. From this table it can be seen that a large percentage of the number of hours of ice or snow in Regions 4 and 5 are due to ice.

A tabulation of the number of fatal, injury, and PDO accidents by region and road condition is given in Table C-7. Only one of the eight fatal crashes recorded in 1968, under ice or snow, occurred on the Interstate System. This fatal crash occurred in Region 5 under icy pavement conditions. Two of the five fatal crashes recorded in 1969, under ice or snow, occurred on the Interstate System. The two took place in Region 4, also under icy conditions.

Virginia

Four years of accident data, covering the years 1965 through 1968, were obtained from the Virginia Department of Highways for a specific divided Interstate bridge. The bridge is located on the I-95 interchange with Route 1 near Spotsylvania, Va. (midway between Washington, D.C., and Richmond, Va.). This bridge was chosen for analysis because of the large number of accidents experienced both on the bridge and in its immediate vicinity during the past several years. The southbound lanes, on which a majority of the accidents have occurred, are located on a righthand curve downstream of a slight downgrade.

The bridge accident data collected were in the form of collision diagrams. Supplemental information was obtained from accident data work sheets. Only those accidents that

TABLE C-1

ESTIMATES OF IOWA ROAD SURFACE EXPOSURE FOR 1966 AND 1969

Year	Region	Number of Hours				
		Ice	Snow	Ice or Snow	Wet	Dry
1966	1	11	129	140	734	7,886
	2	15	61	76	795	7,889
	3	8	68	76	763	7,921
	4	11	50	61	813	7,886
	5	15	60	75	974	7,711
1969	1	7	190	197	850	7,713
	2	26	97	123	1,038	7,599
	3	22	172	194	929	7,637
	4	31	126	157	1,057	7,546
	5	34	123	157	1,066	7,537

TABLE C-2

ACCIDENT DATA FOR ALL BRIDGES IN IOWA DURING 1966 AND 1969

Crashes	Region	1966			1969		
		Ice or Snow	Wet	Dry	Ice or Snow	Wet	Dry
Fatal	1	0	0	3	1	0	3
	2	0	2	2	0	2	4
	3	1	0	5	0	0	0
	4	0	0	7	0	2	6
	5	0	0	3	0	0	3
	Total	1	2	20	1	4	16
Injury	1	5	4	24	10	8	21
	2	9	3	20	8	9	15
	3	7	1	17	18	10	34
	4	4	9	34	24	18	36
	5	2	7	16	5	5	33
	Total	27	24	111	65	50	139
PDO	1	8	1	23	18	15	31
	2	11	10	23	18	10	29
	3	14	3	36	33	27	51
	4	9	7	38	30	22	58
	5	5	6	27	25	22	80
	Total	47	27	147	124	96	249
Total	1	13	5	50	29	23	55
	2	20	15	45	26	21	48
	3	22	4	58	51	37	85
	4	13	16	79	54	42	100
	5	7	13	46	30	27	116
	Total	75	53	278	190	150	404

occurred on the bridge and short segments of the bridge approaches were included in the analysis. A total of 20 accidents was obtained for analysis. Of these 20, 17 accidents occurred in the southbound direction, and 10 occurred during icy and snowy pavement conditions. A breakdown of the number of fatal, injury, and PDO accidents recorded for different pavement conditions is given in Table C-8. Seven people were injured in the six injury accidents recorded. It is interesting also to note that no fatal crashes were recorded during this time interval.

Estimates of the road surface exposure for the bridge are given in Table C-9. These data were obtained from the Local Climatological Data (LCD) reports collected by the weather service station at the Richmond, Va., airport. Excellent agreement was noted between the road conditions reported on the accident forms and the weather environment recorded in Richmond. However, time lags in the weather between the two points were found as expected.

BRIDGE ACCIDENT RATES

Not all of the preceding data were used in quantifying accident rates for use in the illustrative examples of the cost-benefit methodology. Instead, rates were determined

TABLE C-3

ACCIDENT DATA FOR INTERSTATE BRIDGES IN IOWA DURING 1969

Crashes	Region	Ice or Snow	Wet	Dry
Fatal	1	0	0	0
	2	0	0	0
	3	0	0	0
	4	0	0	4
	5	0	0	1
	Total	0	0	5
Injury	1	1	3	0
	2	0	0	0
	3	7	6	16
	4	12	10	14
	5	1	1	1
	Total	21	20	31
PDO	1	3	4	3
	2	1	0	0
	3	13	16	18
	4	16	9	25
	5	6	2	6
	Total	39	31	52
Total	1	4	7	3
	2	1	0	0
	3	20	22	34
	4	28	19	43
	5	7	3	8
	Total	60	51	88

TABLE C-4

ESTIMATES OF OHIO ROAD SURFACE EXPOSURE FROM APRIL 1968 THROUGH MARCH 1970

		Number of Hours				
Year	Region	Ice	Snow	Ice or Snow	Wet	Dry
April 1968	1	7	201	208	1,416	7,136
through	2	13	95	108	1,407	7,245
March 1969	3	10	239	249	1,453	7,058
	4	11	69	80	1,596	7,084
	5	5	67	72	1,423	7,265
April 1969	1	18	228	246	1,249	7,265
through	2	11	119	130	1,299	7,331
March 1970	3	25	289	314	1,355	7,091
	4	17	195	212	1,371	7,177
	5	23	136	159	1,188	7,413

from a sample of the data that still reflect the different climatic conditions and winter maintenance practices that exist in various areas. Before proceeding with a description of the sample data used and rates computed, two items should be discussed. These are the fraction of time that localized ice or snow conditions exist and the fraction of bridge accidents that occur under localized icing conditions.

There are three major types of localized bridge icing: frost, times at the beginning and endings of storms, and refreeze of melt runoff. Contacts with several state highway departments and a review of the literature revealed that very little data exist (or are conveniently available) on the extent and/or frequency of localized bridge icing conditions. Some data are available on bridge deck frosting frequency for two areas (*10, 12*). However, no data were found either on the other types of localized icing conditions or on a procedure for estimating localized and generalized bridge icing exposure times.

In addition, no reliable data were found during the searches on the number of accidents occurring under localized icing conditions. A cursory examination of the computerized bridge accident data was made to determine if

TABLE C-5

ACCIDENT DATA FOR ALL BRIDGES IN OHIO FROM APRIL 1968 THROUGH MARCH 1970

		April 1968 through March 1969			April 1969 through March 1970		
Crashes	Region	Ice or Snow	Wet	Dry	Ice or Snow	Wet	Dry
Fatal	1	0	0	0	0	0	0
	2	0	0	6	0	0	3
	3	0	0	0	0	0	2
	4	4	1	4	2	0	8
	5	0	0	2	0	1	5
	Total	4	1	12	2	1	18
Injury	1	3	1	5	8	1	2
	2	16	15	36	29	16	35
	3	7	3	6	5	4	8
	4	18	16	48	32	22	68
	5	6	3	20	4	10	19
	Total	50	38	115	78	53	132
PDO	1	0	0	2	4	1	0
	2	15	6	22	34	14	28
	3	4	3	4	10	3	4
	4	18	14	38	47	15	46
	5	4	10	15	6	11	20
	Total	41	33	81	101	44	98
Total	1	3	1	7	12	2	2
	2	31	21	64	63	30	66
	3	11	6	10	15	7	14
	4	40	31	90	81	37	122
	5	10	13	37	10	22	44
	Total	95	72	208	181	98	248

TABLE C-6

ESTIMATES OF TEXAS ROAD SURFACE EXPOSURE FOR 1968 AND 1969

		Number of Hours				
Year	Region	Ice	Snow	Ice or Snow	Wet	Dry
1968	1	11	46	57	707	8,020
	2	9	40	49	685	8,050
	3	12	44	56	956	7,772
	4	13	6	19	1,104	7,661
	5	13	0	13	1,211	7,560
1969	1	1	71	72	860	7,828
	2	4	65	69	717	7,974
	3	28	34	62	940	7,758
	4	5	0	5	966	7,789
	5	5	0	5	930	7,825

any of the icy or snowy bridge accidents recorded could have taken place during localized icing. By sorting the data by time of day (early morning hours) and weather (clear), a few accidents were noted that could have occurred during frosty conditions. However, insufficient information was available to positively identify the accidents as frosty bridge accidents. Likewise, the data did not provide enough detail to identify accidents under the other two types of localized icing conditions. Additional connective data, such as local weather data (for the specific bridge accident location) or the actual accident report, would be required before positive identification could be made of accidents occurring under localized icing conditions. No effort was made to collect this additional information. The attempt to isolate localized icy bridge accidents from the available accident data was subsequently abandoned.

TABLE C-7

ACCIDENT DATA FOR ALL RURAL BRIDGES IN TEXAS DURING 1968 AND 1969

		1968			1969		
Crashes	Region	Ice or Snow	Wet	Dry	Ice or Snow	Wet	Dry
Fatal	1	0	0	0	1	0	0
	2	1	0	1	0	1	0
	3	0	0	3	1	0	3
	4	5	6	50	3	10	36
	5	2	7	46	0	7	23
	Total	8	13	100	5	18	62
Injury	1	3	2	5	10	3	7
	2	2	0	6	0	5	9
	3	3	6	23	5	5	27
	4	52	66	244	25	73	247
	5	40	74	220	1	63	259
	Total	100	148	498	41	149	549
PDO	1	4	0	14	12	6	7
	2	10	4	4	2	10	8
	3	13	12	34	11	10	32
	4	188	143	354	94	159	378
	5	200	185	480	8	202	538
	Total	415	344	886	127	387	963
Total	1	7	2	19	23	9	14
	2	13	4	11	2	16	17
	3	16	18	60	17	15	62
	4	245	215	648	122	242	661
	5	242	266	746	9	272	820
	Total	523	505	1,484	173	554	1,574

TABLE C-8

ACCIDENT DATA FOR A BRIDGE ON THE I-95 INTERCHANGE WITH ROUTE 1 NEAR SPOTSYLVANIA, VIRGINIA

	Ice or Snow				Wet				Dry			
Year	Fatal	Injury	PDO	Total	Fatal	Injury	PDO	Total	Fatal	Injury	PDO	Total
1965	0	0	0	0	0	0	1	1	0	0	1	1
1966	0	2	4	6	0	1	0	1	0	0	1	1
1967	0	0	0	0	0	1	0	1	0	0	1	1
1968	0	0	4	4	0	1	0	1	0	1	2	3
Total	0	2	8	10	0	3	1	4	0	1	5	6

Instead, recourse was made to estimating hours of exposure and accidents occurring under localized icing conditions from new data collected on a sampling basis.

Special Winter Maintenance Data

The maintenance departments of six states contacted agreed to collect special winter maintenance data during the 1972-1973 winter on specific bridges. The states that participated in this effort were Illinois, Iowa, Michigan, Ohio, Texas, and Virginia. Personal visits were made to each of these states to describe the project objectives and to discuss specifically the data collection with the local maintenance foremen selected. The data collected pertained to the treatment of various bridge deck conditions in addition to the hours of bridge deck exposure to the various road surface conditions, including times of localized icing.

Maintenance data collection forms were developed and distributed to ensure a consistency of reporting. One form, "Bridge Condition and Maintenance Operation Report Related to Frost, Ice and Snow Control," is shown in Figure C-1. This form was to be filled out by the local maintenance foreman each time there was any maintenance ac-

TABLE C-9

ESTIMATES OF ROAD SURFACE EXPOSURE FOR BRIDGE ON I-95 IN VIRGINIA

	Number of Hours				
Year	Ice	Snow	Ice or Snow	Wet	Dry
1965	0	70	70	910	7,780
1966	29	80	109	1,103	7,548
1967	35	35	70	1,077	7,613
1968	18	32	50	1,077	7,657

tivity on the monitored bridge(s). This report asks for such information as bridge and approach pavement conditions, meteorological conditions, time and type of maintenance treatment, and duration of various bridge deck conditions after treatment began. A second form, "Bridge Deck Characteristics," is shown in Figure C-2 and was to be filled out once for each bridge monitored. This latter form asks for specific construction and geometric details of the bridge and its surroundings.

The road exposure data requested were collected for a specific bridge in one, two, or three maintenance areas of each state. A total of 21 bridges of varying characteristics were involved in the study. Four of these bridges were selected to serve as a control for four companion structures. The control bridges carried little traffic and consequently had low winter maintenance on them. Initially, it was intended that the data from the control structures would be compared with the corresponding high maintenance bridges to determine the effect of traffic and local maintenance practice on localized bridge icing. This comparison was not possible because of the small amount of control data recorded. Almost no data were recorded for two of the control structures, and no localized icing conditions were observed on a third structure.

The maintenance data collected were completely reviewed, and tabulations were made of specific items of interest. The frequency of localized icing conditions for each bridge area is given in Table C-10 along with the number of maintenance treatments for localized and generalized conditions. The frequency of occurrence of localized bridge icing conditions is seen to be quite variable for different parts of the U.S. and also for different areas within a state. Data from Table C-10 were used in the numerical examples of Appendix H to show the geographical influence upon the cost-benefit results. No attempt was made to combine the bridge deck characteristics data with the frequency data to assess the factors responsible for localized icing conditions.

The extent of localized bridge icing conditions was computed from the maintenance data taken collectively. The number of hours of localized icing conditions recorded was found to be one-quarter of the total hours of ice and snow reported. The times involved in the computations include the time from the start of precipitation to the point when maintenance was first aware of the condition plus the time the pavement condition persisted after maintenance was alerted. The effects of frost were not included in computing the hours of exposure. The data recorded on frost duration are not considered very accurate because of the difficulties in manually observing the condition. Frost is generally of short duration under natural conditions and, especially, when exposed to traffic and abrasive/deicing agents. The duration of frost for most areas is a small fraction of the time estimated for localized ice and snow conditions. Thus, little error is made by neglecting the exposure time due to frost. This is the approach followed in Appendix E.

The following assumptions were used in extending the foregoing results to estimating the hours of exposure for a given location:

1. The number of hours of localized icing conditions is assumed to be one-quarter of the total hours of ice and snow obtained from LCD weather records according to the method discussed in Appendix E.
2. The number of hours of generalized icing conditions is assumed to be three-quarters of the total hours of ice and snow.

Special Bridge Accident Data

Special bridge accident data were collected during the 1972-1973 winter by the highway patrols in five states: Iowa, Kansas, Missouri, Texas, and Virginia. The areas of data collection are as follows:

Iowa—Posts 11 and 12, which include 12 counties in east-central Iowa.

Kansas—Whole state.

Missouri—Troup A, which includes part of Kansas City, Missouri, and 13 surrounding counties.

Texas—31-county area of the Texas Panhandle.

Virginia—9-county area surrounding and including I-95 from Fredricksburg to Petersburg, Va., plus the toll road from Richmond to Petersburg, Va.

A special form was developed which would be completed by the field officers (in addition to the standard accident report) for each bridge accident investigated, regardless of the pavement conditions. The special report form is shown in Figure C-3. This form makes a distinction between frosty and icy bridge deck conditions and contains a provision for recording whether the icy condition was localized or generalized in nature. Connective information was also recorded so that additional data describing the details of the accident could be extracted from the official accident report.

At the end of the 1972-1973 winter, the five highway patrols were asked to submit the special bridge accident data along with copies of the actual accident reports. All of the special data requested was returned; however, not all of the actual accident reports could be made available to the project because of legal restrictions. Consequently, it was not possible to conduct a thorough analysis of the accident data as had been planned. Instead, a tabulation was made of the bridge accident data by pavement condition. These data are given in Table C-11. The percentage of ice and snow bridge accidents that occurred under localized conditions ranged from zero in Iowa to 79.2 percent in Kansas. The weighted percentage of all recorded ice and snow accidents that occurred under localized conditions was 43.2 percent. Only 21 of the accidents recorded in the 1972-1973 winter under localized ice and snow conditions were reported to be due to frost; five of these occurred in Kansas and 16 were recorded in Missouri.

BRIDGE CONDITION AND MAINTENANCE OPERATION
REPORT RELATED TO FROST, ICE AND SNOW CONTROL

1. Date _____, 197_____

2. County _____ Foreman _____

3. Bridge Number _____ High Maintenance _____ Low Maintenance _____
----------(Check One)----------

4. Route Number _____

5. Maintenance Activity
   - ○ Routine Inspection of Bridge
   - ○ Frost Control
   - ○ Ice and Snow Control

6. Time First Aware of Bridge Deck Condition _____ a.m. / p.m.

Pavement Conditions at Inspection or Beginning of Maintenance Operation

7. Bridge Deck Condition
   ○ Dry ○ Wet ○ Frost ○ Ice ○ Snow ○ Slush

   Bridge Deck Coverage
   ○ Spotty ○ Uniform ○ Drifting

8. Approach Pavement Condition
   ○ Dry ○ Wet ○ Frost ○ Ice ○ Snow ○ Slush

   Approach Pavement Coverage
   ○ Spotty ○ Uniform ○ Drifting

9. Sky Condition at Inspection or Beginning of Maintenance Operation
   ○ Clear ○ Partly Cloudy ○ Overcast ○ Fog

10. Type of Precipitation at Inspection or Beginning of Maintenance Operation (Check One or More)
    ○ None ○ Drizzle ○ Rain ○ Fr. Rain ○ Sleet ○ Lt. Snow ○ Snow ○ Blow Snow ○ Other*

11. Rainfall _____ In., Started _____ a.m. / p.m. Duration _____ Hr

12. Snowfall _____ In., Started _____ a.m. / p.m. Duration _____ Hr

13. Estimated Meteorological Conditions at Inspection or Beginning of Maintenance Operation
    Wind Speed: ○ 0-5 mph ○ 5-15 mph ○ 15+ mph

13. (Concluded)
    Wind Direction From: ○ No Wind ○ N ○ NE ○ E ○ SE ○ S ○ SW ○ W ○ NW

    Air Temperature _____ °F

14. Maintenance Treatment of Bridge Deck (Check One or More)
    - ○ None
    - ○ Plowing
    - ○ Applying Rock Salt
    - ○ Applying Abrasives
    - ○ Applying Mixture of Rock Salt and Abrasives
    - ○ Applying Mixture of Calcium Chloride and Abrasives
    - ○ Applying Mixture of Salt and Calcium Chloride
    - ○ Other (Specify) _____

15. Time of Maintenance Treatment _____ a.m. / p.m.

16. Mixture Ratio

    _____ Parts Salt; _____ Parts Calcium Chloride; _____ Parts Abrasives

17. Application Rate: _____ Lb/Lane-Mile

18. Estimated Length of Time (In Tenths of Hours) For Various Bridge Deck Conditions After Treatment Began:

Frosty	_____ Hr	Snow Packed	_____ Hr
Icy	_____ Hr	Slush	_____ Hr
Localized Icy	_____ Hr	Wet	_____ Hr
Icy in Spots	_____ Hr		

19. Estimated Traffic Count During Frost, Ice and Snow Control

    _____ Number of Vehicles Per _____ Min

20. *Remarks and Comments

    For any accidents that occur at the bridge location, please record the time, date, bridge deck and approach pavement conditions at the time of the accident.

Figure C-1. Form I—Bridge condition and maintenance operation report related to frost, ice, and snow control.

BRIDGE DECK CHARACTERISTICS

The following data are to be recorded once for each bridge monitored during the 1972-73 winter.

1. Bridge Number_____High Maintenance_____Low Maintenance_____
   ----------(Check One)----------
2. Location:
   State_____
   County_____
   Route No. _____
   Area Type ○ Rural ○ Urban ○ Suburban
3. Average Annual Daily Traffic (AADT) Crossing This Bridge _____
4. Estimated Average Daily Traffic (ADT) Crossing This Bridge in Winter Months_____
5. Posted Speed Limit _____mph
6. Traffic Flow on This Bridge: ○ 1-way ○ 2-way
7. Number of Lanes on This Bridge _____
8. Type of Crossing (Check One or More)
   ○ Water ○ Dry Ground ○ Railroad ○ Major Road ○ Minor Road ○ Buildings
9. Surrounding Terrain Characteristics: ○ Mountainous ○ Rolling ○ Flat
10. Bridge Type:
    ○ Continuous Concrete Slab
    ○ Steel Girder
    ○ Prestressed Concrete Girder
    ○ Concrete Box Girder
    ○ Concrete T Girder
    ○ Girder and Floor Beam System
    ○ Truss and Floor Beam System
    ○ Other (Specify) _____
11. Type of Superstructure: ○ Through Bridge ○ Deck Bridge
12. Bridge Railing Design: ○ Solid Parapet ○ Open Steel
13. Bridge Deck Surface Type
    ○ Portland Cement Concrete
    ○ Portland Cement Concrete with Asphalt Overlay
    ○ Asphaltic Concrete
    ○ Other (Specify) _____
14. Special Bridge Deck Surface Coating
    ○ Epoxy
    ○ Linseed Oil
    ○ None
    ○ Other (Specify) _____
15. Approach Pavement Surface Type
    ○ Portland Cement Concrete
    ○ Portland Cement Concrete with Asphalt Overlay
    ○ Asphaltic Concrete
16. Condition of Bridge Deck Surface (Check One or More)
    ○ No Evidence of Deterioration
    ○ Spalling
    ○ Smooth or Polished Surface
    ○ Rutted
    ○ Low Areas Where Water Collects
17. Average Bridge Deck Thickness _____Inches
18. Bridge Length _____Feet
19. Percent of Grade at Each End of Bridge:
    Upstream _____% Up/Down Grade; Downstream _____% Up/Down Grade
20. Minimum Horizontal Radius of Curvature of Bridge _____ Feet
    (Or Check ○ if Tangent)
21. Superelevation of Bridge _____ Feet Per Foot of Width
22. Average Elevation of Bridge Deck Surface Above Terrain Crossed _____ Feet
23. Primary Orientation of Bridge
    ○ N-S ○ NE-SW ○ E-W ○ SE-NW

Completed By _____ Location _____

Figure C-2. Form II—Bridge deck characteristics.

TABLE C-10

MAINTENANCE DATA COLLECTED ON BRIDGE ICING CONDITIONS DURING 1972-1973 WINTER

Bridge Area	Time Period	Number of Localized Conditions			Number of Maintenance Trips	Number of Maintenance Treatments	
		Frost	Ice, Snow	Total		Localized	General
Illinois							
Effingham	12/27/72 - 2/18/73	2	0	2	6	2	4
East St. Louis[a]	11/19/72 - 2/28/73	2	1	3	49	3	46
Iowa							
Knoxville	12/11/72 - 2/14/73	1	0	1	14	1	13
Ames	12/11/72 - 4/10/73	8	1	9	49	9	40
Iowa City	11/2/72 - 2/17/73	3	0	3	22	3	19
Michigan							
Lansing	11/20/72 - 4/10/73	9	6	15	18	15	3
Lansing	12/1/72 - 4/10/73	9	4	13	17	13	4
Saginaw	1/3/73 - 1/21/73	3	0	3	4	3	1
Saginaw	12/11/72 - 2/13/73	6	0	6	7	6	1
Ohio							
Ravenna	12/4/72 - 4/10/73	1	1	2	141	6	134
Ravenna[b]	12/8/72 - 4/10/73	1	3	4	107	12	94
Columbus[a]	12/8/72 - 4/12/73	0	7	7	43	16	27
Cleveland	12/8/72 - 3/17/73	0	0	0	17	0	17
Texas							
Amarillo	1/2/73 - 4/6/73	1	10	11	24	11	13
Lubbock	1/2/73 - 2/22/73	0	0	0	36	0	36
Lubbock[b]	1/2/73 - 2/22/73	0	0	0	36	0	36
Virginia							
Wytheville	1/3/73 - 3/21/73	0	1	1	14	1	13
Staunton	12/21/72 - 2/1/73	0	1	1	7	1	6
Fredericksburg	1/8/73 - 2/27/73	0	0	0	2	0	2

a/ No detailed data are available for the companion control structure.
b/ Control structure.

The following assumptions were used in extending the preceding results to icy and snowy bridge accidents in general:

1. The number of bridge accidents under *localized* icing conditions is 43.2 percent of the numbers recorded in the accident data for ice and snow combined. (This fraction is in reasonable agreement with the results of a study (*16*) wherein about one-third of the icy highway accidents on the Pennsylvania Turnpike were attributable to unexpected icy conditions (such as icy spots).) This percentage is also assumed to apply uniformly to all accidents, regardless of severity.

2. The number of bridge accidents under *generalized* icing conditions is 56.8 percent of the numbers recorded in the accident data for ice and snow combined.

Bridge Accident Rates

Bridge accident rates for each of the five pavement conditions (localized and generalized ice or snow, abrasives on ice, wet and dry) were computed from a sample of the data presented earlier in this appendix, employing the foregoing and following assumptions. The accident rate for localized icing conditions is assumed to be 2.28 times the generalized rate. Also, the accident rate for abrasives on ice is assumed to be the arithmetic average of the rates for generalized ice or snow and wet conditions. This last assumption is made based on engineering judgment in the absence of definitive data.

The resulting samples of bridge accident rates are given in Tables C-12 through C-16, as number per hour of exposure.

The regions selected from each of three states were chosen by considering both the accident experience under ice or snow and also the spread in the number of hours of exposure of ice or snow. There are 909 bridges in Iowa Region 4, which include 40 pairs of Interstate bridges. There are about 550 bridges in Ohio Region 3; however, accidents were recorded on only 27 of these bridges between April 1969 through March 1970. Texas Region 1 contains approximately 1,000 bridges. The rates given in Table C-16 are average (yearly) values obtained from the 4 years of accident data. The rates in the other tables are on a yearly basis. The rates given in these five tables were used in the illustrative examples of the cost-benefit methodology discussed in Appendix H.

RELATIONSHIP BETWEEN ACCIDENT RATES AND EXPOSURE TIME

A subsidiary analysis of the statewide bridge accident data was performed using the data collected from Iowa, Ohio, and Texas. The purpose of this investigation was to determine if a correlation exists between relative accident rates (defined differently from the foregoing) and exposure times. Two years of bridge accident data (both the total number of accidents and the number under icy or snowy conditions) and the total number of hours of exposure to ice or snow, N, for each of the 15 regions were used in the analysis. This produced an original sample size of 30 region-years. No distinction was made between the levels of severity of the accidents (i.e., a fatality accident, regardless of the number of people killed in the accident, was counted the same as a property-damage-only accident). In addition, the number of hours of ice or snow was not subdivided between localized and generalized conditions.

The 15 regions differ widely in the total number of bridge accidents recorded per year (they ranged from 11 to 1,254 accidents). Therefore, the ratio, A, of the number of ice or snow accidents to the total number of accidents, expressed in percent, was computed for each region-year:

$$A = \frac{100 \times (\text{number of ice, snow accidents})}{(\text{total number of accidents})} \qquad \text{(C-1)}$$

Regions with less than 30 total accidents and/or less than 10 ice or snow accidents were eliminated from the data because of the small sample size. This reduced the number of region-years considered from 30 to 22.

Next, a relative ice or snow accident rate, R, was computed from

$$R = 10\,A/N \qquad \text{(C-2)}$$

for each region-year. The factor of 10 was inserted in Eq. C-2 for convenience. The values of N, A, and R for each of the 22 region-years of study are given in Table C-17.

The Spearman rank correlations, r_s, of the data in Table C-17 were computed (note that this correlation is analogous to the simple correlation, r, except that the Spearman rank

BRIDGE ACCIDENT REPORT SUPPLEMENT

Definition: For this investigation, a bridge accident is any accident that results from a driver loosing control on the bridge (regardless of the final collision point) or any accident wherein the bridge is involved in any other way.

ACCIDENT DESCRIPTORS

Date _____ Time _____ AM ○ PM ○ MIL ○

Route No. _____ Postmile _____

County _____ Accident Record No. _____

Bridge No. _____

PAVEMENT CONDITIONS (at time of accident)

BRIDGE DECK CONDITION
Dry ○
Wet ○
Frost ○
Ice ○
Snow ○
Slush ○

APPROACH PAVEMENT CONDITION
Dry ○
Wet ○
Frost ○
Ice ○
Snow ○
Slush ○

COVERAGE
Spotty ○
Uniform ○
Drifting ○

COVERAGE
Spotty ○
Uniform ○
Drifting ○

EVIDENCE OF HIGHWAY MAINTENANCE ON BRIDGE
(Check One or More)

Plowed ○ Salted ○ Sanded ○ Other Deicer ○ None ○

Figure C-3. Bridge accident report supplement.

TABLE C-11

SAMPLE OF BRIDGE ACCIDENT DATA RECORDED DURING 1972-1973 WINTER

State	Total	Dry	Wet	Generalized Ice, Snow	Localized Ice, Snow	Percent Ice, Snow Accidents Under Localized Conditions
Iowa	27	7	8	12	0	0.0
Kansas	26	2	0	5	19	79.2
Missouri	109	42	17	32	18	36.0
Texas	29	11	2	11	5	31.3
Virginia	35	12	14	3	6	66.6
Total	226	74	41	63	48	43.2

TABLE C-12

1969 ACCIDENT DATA FOR 909 BRIDGES IN IOWA REGION 4

Surface Condition	Exposure (hr)	Number Accidents	Rates (Number Accidents Per Hours of Exposure)
Localized Ice, Snow	39	23.3	0.597
Generalized Ice, Snow	118	30.7	0.260
Abrasives on Ice	-	-	0.149
Wet	1,057	42	0.0397
Dry	7,546	100	0.0133

TABLE C-13

1969 ACCIDENT DATA FOR 80 INTERSTATE BRIDGES IN IOWA REGION 4

Surface Condition	Exposure (hr)	Number Accidents	Rates (Number Accidents Per Hours of Exposure)
Localized Ice, Snow	39	12.1	0.310
Generalized Ice, Snow	118	15.9	0.135
Abrasives on Ice	-	-	0.0765
Wet	1,057	19	0.0180
Dry	7,546	43	0.00570

TABLE C-14

ACCIDENT DATA FOR 550 BRIDGES IN OHIO REGION 3 FOR PERIOD APRIL 1969 THROUGH MARCH 1970

Surface Condition	Exposure (hr)	Number Accidents	Rates (Number Accidents Per Hours of Exposure)
Localized Ice, Snow	78	6.5	0.0834
Generalized Ice, Snow	236	8.5	0.0360
Abrasives on Ice	-	-	0.0206
Wet	1,355	7	0.00517
Dry	7,091	14	0.00198

TABLE C-15

1969 ACCIDENT DATA FOR 1,000 BRIDGES IN TEXAS REGION 1

Surface Condition	Exposure (hr)	Number Accidents	Rates (Number Accidents Per Hour of Exposure)
Localized Ice, Snow	18	9.9	0.550
Generalized Ice, Snow	54	13.1	0.243
Abrasives on Ice	-	-	0.127
Wet	860	9	0.0105
Dry	7,828	14	0.00179

TABLE C-16

AVERAGE ACCIDENT DATA FOR AN INTERSTATE BRIDGE ON I-95 IN VIRGINIA FOR THE YEARS 1965-1968

Surface Condition	Exposure (hr)	Number Accidents	Rates (Number Accidents Per Hour of Exposure)
Localized Ice, Snow	18.7	1.1	0.0588
Generalized Ice, Snow	56.1	1.4	0.0250
Abrasives on Ice	-	-	0.0130
Wet	1,042	1	0.000960
Dry	7,650	1.5	0.000196

TABLE C-17

VALUES OF N, A, AND R COMPUTED FOR 22 REGION-YEARS

State	Region	Year	N (hr)	Number of Ice, Snow Accidents	A (%)	R
Iowa	1	1966	140	13	19.1	1.36
Iowa	2	1966	76	20	25.0	3.29
Iowa	3	1966	76	22	26.2	3.45
Iowa	4	1966	61	13	12.0	1.97
Iowa	1	1969	197	29	27.1	1.38
Iowa	2	1969	123	26	25.7	2.09
Iowa	3	1969	194	51	29.5	1.52
Iowa	4	1969	157	54	27.6	1.76
Iowa	5	1969	157	30	17.3	1.10
Ohio	2	1968-1969	108	31	26.7	2.47
Ohio	4	1968-1969	80	40	24.8	3.10
Ohio	5	1968-1969	72	10	16.7	2.32
Ohio	2	1969-1970	130	63	39.6	3.05
Ohio	3	1969-1970	314	15	41.7	1.33
Ohio	4	1969-1970	212	81	33.8	1.59
Ohio	5	1969-1970	159	10	13.2	0.83
Texas	3	1968	56	16	17.0	3.04
Texas	4	1968	19	245	22.3	11.74
Texas	5	1968	13	242	19.3	14.85
Texas	1	1969	72	23	48.9	6.79
Texas	3	1969	62	17	20.7	3.34
Texas	4	1969	5	122	11.9	23.80

correlation is determined from a rank of two sets of data instead of the numerical magnitude of the data):

$(r_s)_{NA} = +0.52$ (exposure versus percent of total accidents that occurred under ice or snow) (C-3a)

$(r_s)_{RN} = -0.82$ (relative accident rate versus exposure) (C-3b)

Thus, although there is some trend towards more accidents under ice or snow with increasing ice or snow exposure time, there is an inverse relationship between ice or snow relative accident rate and ice or snow exposure time. Referring to Table C-17, it can be seen that in 1969 icy or snowy bridges were more dangerous in Central Texas (which had 5 hr of ice or snow with an $R = 23.8$) than in Ohio (which had between 130 and 314 hr of ice or snow with an R value range of between 0.83 and 3.05).

Plots of R vs. N were generated on linear, semilog, and log-log paper. A definite relationship appeared in the log-log plot. Consequently, a regression line

$$\text{Log}\, R = \alpha_0 + \alpha_1 \log N \qquad \text{(C-4)}$$

or

$$R = e^{\alpha_0} N^{\alpha_1} \qquad \text{(C-5)}$$

was fitted to the data and the coefficients α_0 and α_1 were evaluated. The resulting computations yielded

$$R = 99.98\, N^{-0.81} \qquad \text{(C-6)}$$

A plot of the relative accident rate versus hours of exposure to ice or snow is given in Figure C-4 for the 22 region-years (see also Table C-17). The regression line is superimposed on the data. The distribution of the data is seen to be described extremely well by the regression line. The correlation coefficient between R and N was computed and found to be $r = -0.920$ ($r^2 = 0.847$). Thus, 85 percent of the variation in the relative accident rate, R, is explained by N. Of course, the value of N is an estimate of unknown precision, so the 85 percent accountable variation might be somewhat artificial; nevertheless, the curve is believed to be meaningful. For instance, the accident data used include both urban and rural influences, and no distinction is made either for the highway type or for the many variables of the bridges' geometrics. Also, the effect of ADT is not explicitly incorporated in the rate. All of these factors, in combination with the accuracy of the estimate of N, contribute only 15 percent towards explaining the variation between R and N. The foregoing empirical regression line can, therefore, be expected to yield, as a first approximation, the number of accidents in an area under ice or snow conditions, given the total number of bridge accidents and an estimate of the number of hours of exposure to ice or snow.

ESTIMATED YEARLY NUMBER OF BRIDGE ACCIDENTS UNDER LOCALIZED ICING CONDITIONS

There is some interest in estimating the yearly number of bridge accidents that occur throughout the country under localized ice or snow conditions. Currently, no estimate is available in the published literature. However, an approximation can be made from the data collected during this investigation by imposing certain assumptions based on en-

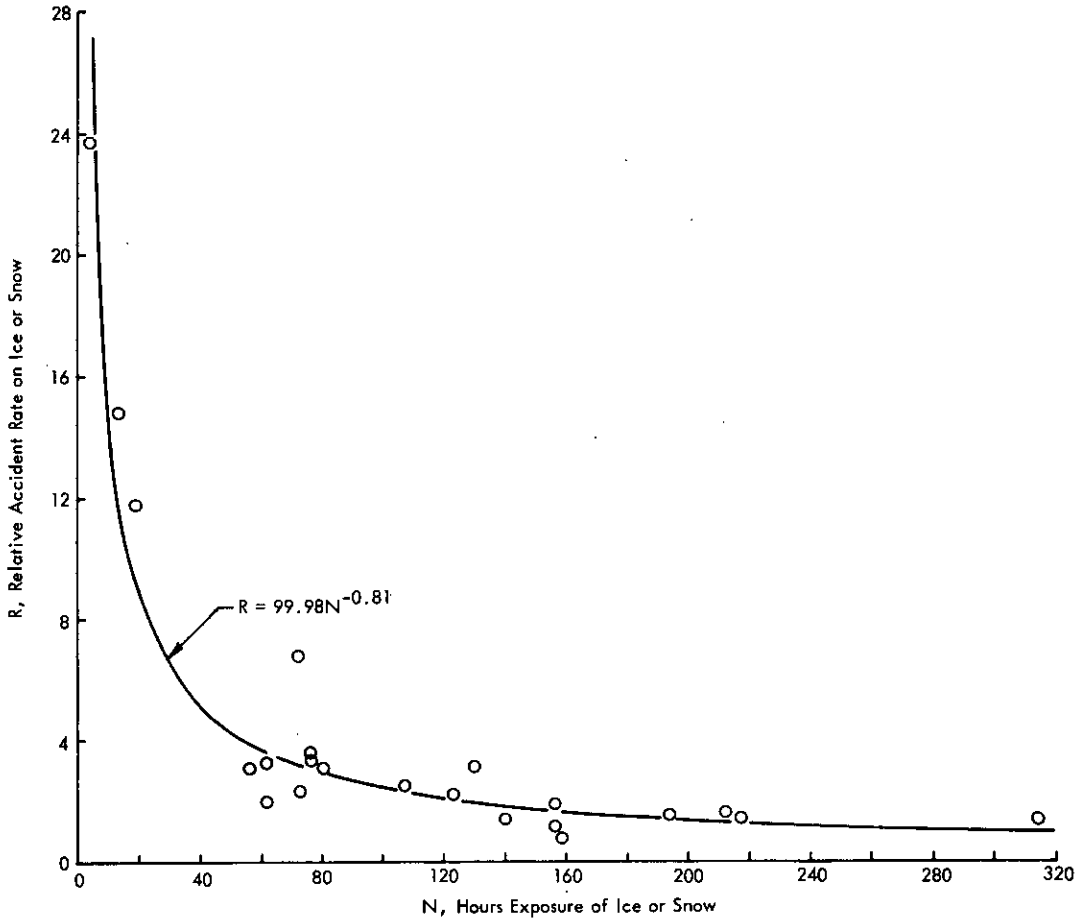

Figure C-4. Relative accident rate vs. hours of exposure to ice or snow.

gineering judgment. The construction of the estimated number of bridge accidents under localized conditions can be determined knowing the following qualities:

1. The total yearly number of accidents.
2. The fraction of total accidents that occur on bridges.
3. The fraction of bridge accidents that occur under ice or snow pavement conditions.
4. The fraction of ice or snow bridge accidents that occur under localized conditions.

According to the National Safety Council's tabulations, there were approximately 15.5 million accidents recorded throughout the U.S. during 1969 (*17*). The preceding items 2 and 3 can be estimated from the data given in Table C-18. On the average, about 1.8 percent of the accidents recorded occurred on bridges. (This figure is an estimate taken from Table C-18, i.e., ½ (0.983 + 2.705) = 1.8%.) This is not an unrealistic number considering that in many areas bridges comprise about 1 percent of the total roadway mileage under jurisdiction of the state highway maintenance departments. Now, if one assumes that the Texas 1969 and Ohio 1969-1970 data for the percent of bridge accidents that occur under ice or snow conditions are symmetrically located on the distribution of this percentage factor, then the average percent of bridge accidents under ice or snow is simply

$$\tfrac{1}{2}\ (7.6 + 34.3) = 21\%$$

The estimation of the fourth item has already been established earlier in this appendix. In other words, 43 percent of all ice or snow bridge accidents are assumed to occur under localized conditions.

Now, combining the foregoing numbers, it is estimated that about

$$15.5 \times 10^6\ (0.018)(0.21)(0.43)$$

or, 25,000 accidents occur annually on bridges because of localized ice, snow, or frost conditions. It would be unfair at this time to hazard a guess about how these accidents are broken down by severity. It should be remembered that this number is strictly a "best" estimate, and that the actual number of accidents could be larger or smaller than 25,000.

TABLE C-18

TABULATION OF ACCIDENT DATA FROM VARIOUS SOURCES

Area	Year	Total Number of Accidents Recorded	Number of Bridge Accidents[e]	Percent of Accidents On Bridges	Percent of Bridge Accidents Under Ice, Snow Conditions
Iowa	1966	10,983[a]	406	2.705	18.47
Iowa	1969	15,903[a]	744	2.138	25.54
Ohio	1968-1969	43,356[b]	375	0.865	25.33
Ohio	1969-1970	47,390[b]	527	1.11	34.35
Texas	1968	62,281[c]	2,502	4.02	20.90
Texas	1969	--	2,273	--	7.61
Denver, Colo.	1969	45,000[d]	442	0.983	21.7

a/ Obtained from unpublished National Safety Council data. The data are for controlled access highways and state routes in rural areas.
b/ Obtained from Ohio Department of Highways summaries and includes interstate, FAP and FAS highways in rural areas.
c/ Obtained from unpublished National Safety Council data. The data are for all types of highways in rural areas of the state.
d/ Obtained from Highway Safety Research Institute's (HSRI) data file. The data are for city streets, county, FAS, FAP, and interstate highways predominately in an urban area.
e/ Obtained from searches of computerized accident data.

APPENDIX D

ACCIDENT COSTS

Accident records generally distinguish between three levels of severity: fatalities, injuries, and property damage only (PDO). In addition, the nature of the injuries is sometimes further defined by specifying them as type "a," "b," and "c" injuries. Although there are standard definitions for these types, studies of their relative frequency of occurrence indicate that the definitions are not necessarily applied in a consistent fashion from state to state (see Table D-1).

It is important to consider more than simply the number of accidents; the relative serverities must be accounted for. No better approach has yet been utilized other than to weight them by cost.

Many estimates of accident costs have been made by individual states and independent research organizations, including the National Safety Council (*18-26*). (The Insurance Institute of Highway Safety has also collected accident cost figures; however, their reports contain figures only for low-speed, front and rear end property damage accidents.) The results of these studies have yielded widely divergent values of accident costs. Some variation in accident cost can be expected from one part of the country to another—mainly because of variations in socio-economic conditions. However, these minor variations can not account for the large differences. The true costs of accidents are still a matter of debate.

One of the primary reasons for the large discrepancies in quoted costs is the lack of universal agreement on the basis for determining the costs. For instance, values are reported for cost per accident, cost per vehicle involved in an accident, and cost per individual killed or injured. Moreover, some studies have excluded from the cost of accidents such items as loss of future earnings of persons killed or permanently injured, whereas other studies have included these values. (The cost of future earnings could be almost equal, in some instances, to the other direct costs of a fatal accident.) Finally, some studies are more specific than others in the types of accidents included.

A source of confusion arises when the investigators fail to report explicitly the variables considered in developing

TABLE D-1

MOTOR VEHICLE INJURY PERCENTAGES, BY TYPE, IN 1968 [a]

State	Injury Type a (Severe)	Injury Type b (Moderate)	Injury Type c (Slight)	State	Injury Type a (Severe)	Injury Type b (Moderate)	Injury Type c (Slight)
Arizona	33	28	39	Mississippi	30	30	40
Arkansas	40	26	34	Montana	30	42	28
Colorado	32	35	33	Nebraska	24	49	28
Connecticut	28	27	44	Nevada	22	52	26
Delaware	8	60	32	New Mexico	34	28	38
Florida	30	24	46	New York	15	26	59
Georgia	65	20	15	North Carolina	46	27	27
Hawaii	28	30	41	North Dakota	48	43	9
Idaho	24	29	47	Oklahoma	35	28	37
Illinois	24	33	43	Oregon	28	37	34
Indiana	32	28	40	Rhode Island	9	74	18
Iowa	12	60	28	South Carolina	40	26	34
Kansas	34	36	30	South Dakota	41	35	24
Kentucky	23	53	24	Virginia	63	12	26
Maine	32	36	32	Wisconsin	22	36	42
Michigan	30	24	45	Wyoming	28	44	28

a/ From unpublished data from the National Safety Council, for all states supplying data consistent with this table. All accidents within the state are included.

the cost estimates. For example, a report by Fleischer (*27*) gives direct costs for traffic-related death and injury as follows:

Source	*Cost of Injury*	*Cost of Death*
California (1967)	$2,300	$9,000
Illinois (1958)	821	5,061
Massachusetts (1953)	862	5,213
Utah (1955)	1,277	3,690

The author obtained these data from a paper by Smith and Tamburri (*25*). However, the data are not, as implied, the costs of an injury or a death. Rather, the California, Massachusetts, and Utah data are costs per injury or fatal *accident,* whereas the Illinois data are costs per *vehicle* involved in an injury or fatal accident. Moreover, the use of the word "direct" is not altogether consistent.

In the final analysis, a set of accident costs must be chosen when making economic comparisons of accident countermeasures. These costs should be reasonably accurate and should reflect the accident experience associated with the roadway conditions of interest. An important item in the practical analysis of safety projects is the relative comparisons of benefits derived from a number of proposals. Valid comparisons can only be made when the same cost figures are uniformly applied to each proposal. Thus, for a given state, the accident cost figures used in an economic evaluation of the effects of ice and frost on bridge decks should be the same as those used to evaluate other safety measures.

In 1966, the National Safety Council published a report containing estimates of 1967 average accident costs (*19*). Modifications are suggested for each of the states to account for differences in income. Yearly increases in these costs are also presented on the basis of trends from 1955 to 1965. These increases amount to 2.5 to 3 percent per year, except for property damage accidents where the rate is substantially less. These projections are not accurate now because of the greater rate of increase in the cost of living, the higher than average increase in hospital and medical costs, and the increasingly liberal attitude of the courts in damage settlements. By the same token, other actions, such as new vehicle safety features and proposed new insurance laws and agreements, may have pronounced effects on such costs. (In 1968 the total cost of motor vehicle injuries and deaths, including future earning losses was $7.5 billion, of which $3.8 billion comprised insurance administrative costs (*29*); in 1969 the total costs were estimated at $7.9 billion of which $3.9 billion comprised insurance administrative costs (*17*).)

Because of the changeable nature and difficulty in forecasting of accident costs, the most recent available data were obtained from the National Safety Council. These are given in Table D-2 for the years 1968 and 1969 (*28*).

The data in Table D-2 include estimates only for death, disabling injury, and PDO accidents. The National Safety Council has stopped making estimates of a, b, and c types of injuries. This designation has been misused by some

TABLE D-2

AVERAGE COSTS ASSOCIATED WITH MOTOR VEHICLE ACCIDENTS, BY SEVERITY [a]

	1968	1969
Cost of a death (per person)	$38,700	$41,700
Cost of a nonfatal (disabling) injury (per person)	2,300	2,500
Cost of property-damage-only accident	360	380

a/ According to National Safety Council estimates.

states, and inaccurate accident data (see Table D-1) have resulted. Furthermore, it is doubtful that accurate cost estimates can be obtained for the a, b, and c types of injury categories, because the incremental change in the cost of a disabling injury during more recent years has been larger than that forecasted in 1966 (*19*).

In 1971 the U.S. Department of Transportation adopted, as an interim measure, the National Safety Council's 1969 estimated accident costs to be used in evaluating and comparing the various safety programs within NHTSA (*30*). The purpose in doing so was based on the need for consistency within the agency; the need for precision in the estimates was not as vital.

The National Safety Council's estimate of the cost of death or disabling injury includes medical expenses, insurance administration costs, the loss of present wages (in the case of death also the loss of expected future wages minus the amount that the victim would spend on himself during his expected lifetime), and property damage to the vehicle and other equipment damaged in the accident (such as light poles, traffic signals, guardrails, etc.). The total cost does not include legal fees or court costs.

The average cost of the property damage included in the cost of death or injury is determined from: (1) estimates made, using sampling techniques, of the property damage costs incurred in both fatal and injury accidents, and (2) the average number of deaths per fatal accident and the average number of injured per injury accident. In a fatal accident, the vehicle is assumed to be a total loss.

The cost of a PDO accident includes the property damage to the vehicles and other equipment damaged in the accident. This average cost is per accident regardless of the number of vehicles involved in the accident. The value is determined from an estimate of the total property damage for all nonfatal, noninjury accidents and the number of PDO accidents.

Analysis of the National Safety Council's suggested accident cost estimates shows that they are low compared to those obtained by other investigators. This may be because the National Safety Council's costs are developed from accidents on all types of highways, in both urban and rural areas, and under all types of weather conditions. Since most recorded accidents occur in an urban or metropolitan area, the National Safety Council's estimates tend to weight more heavily on the "fender bender" types of accidents rather than on the more severe highway accidents. This is likely to be most important in regard to property damage or injury figures.

In a recent NHTSA study (*31*), estimated societal costs of motor vehicle accidents were developed to supersede those previously adopted. These cost values are given in Table D-3.

Another source of accident cost data is contained in a report on the Washington Area Motor Vehicle Accident Cost Study (WAMVACS) (*23*). This study was issued in 1966 and covered the Washington, D.C., area in addition to small contiguous areas of Maryland and Virginia. Both costs per accident by severity and costs per fatality, injury, and PDO can be obtained. The average costs of a fatality, an injury, and a PDO accident are found to be $63,465, $1,159, and $193, respectively. These figures were obtained from a sample size of 202 fatalities, 21,477 injuries, and 67,010 PDO accidents. Ten factors were considered in determining the costs of PDO accidents, ranging from damage to the involved vehicle to legal and court costs associated with the property loss. Fourteen additional cost elements were considered in determining fatality and injury costs. These included hospital and lost-work-time costs in addition to the value of loss of future earnings. The $63,465 cost per fatality is higher than the National Safety Council's figure.

TABLE D-3

AVERAGE SOCIETAL COST OF MOTOR VEHICLE ACCIDENTS

Cost of a fatal accident	$234,960
Cost of an injury accident	11,200
Cost of a property - damage only - accident	500
Average cost per accident	2,800

Accident cost estimates determined by other investigators are given in Table D-4 for comparison purposes. Estimated average accident costs in 1969 were determined by Tamburri and Smith (*18*), using the results of previous studies made by the highway departments of Illinois; Washington, D.C.; and California. These values are presented as a function of accident severity and highway type for both urban and rural areas. The estimates include present worth of future earnings of persons killed or permanently disabled. The costs for "fatal plus injury" (where the two categories are combined but not distinguished) and "all" (combined fatal, injury, and PDO) can be computed by using available accident percentage distributions by severity. The injury accident costs quoted do not distinguish between a, b, or c types of injury.

In the benefit model all accident types of severities are combined into one group, namely accidents. This permits the use of an average cost per accident in evaluating the benefits. It also removes the sensitivity of the benefit result from the presence or absence of fatal crashes under ice or snow conditions.

A detailed analysis of the average cost of bridge accidents showed the costs to be dependent on surface conditions. An average cost of bridge accidents for ice or snow, wet, and dry surface conditions was computed using a large regional mix of fatal, injury, and property-damage-only accidents. Bridge accident data from Texas for 1968 and 1969 (Table C-7), from Ohio for 1968 and 1969 (Table C-5), and from Iowa for 1966 and 1969 (Table C-2) were combined with the rural accident costs per accident reported by Tamburri and Smith (*25*) in computing the average bridge accident cost for the three pavement conditions. Rural accident cost data were selected because a preponderance of the bridge accident data collected were from this type of area. The results of these computations are

TABLE D-4

ACCIDENT COSTS PER ACCIDENT (*18*)

Highway Type	Fatal	Injury	Fatal & Injury	PDO	All
Rural					
2-lane	$95,000	$3,000	$ 8,800	$1,000	$4,600
3-lane			10,500		5,000
4 or more undivided			6,700		3,400
4 or more divided			7,800		3,900
Divided expressway			9,500		4,800
Freeway			10,100		5,300
Urban					
2-lane	$76,000	$2,400	$ 4,000	$ 700	$1,800
3-lane			4,800		1,900
4 or more undivided			3,700		1,700
4 or more divided			3,700		1,700
Divided expressway			4,900		2,300
Freeway			4,300		2,200

given in Table D-5. A sample size of 1,237 ice and snow, 1,432 wet, and 4,196 dry pavement bridge accidents is included in these costs.

The accident cost figures given in Table D-5 are used in the examples of cost-benefit analysis presented in this report. The cost estimates given in Table D-5 do not necessarily represent recommendations; they were used in the examples for illustrative purposes only. If a given state highway department has developed its own set of accident cost figures for use in economic evaluations, those figures should be used in place of the ones listed in Table D-5.

Sample calculations of the benefit results in Appendix H were made to illustrate the effects of using a set of accident cost figures different from those given in Table D-4. For instance, using the NHTSA cost data in Table D-3 in combination with the bridge accident data produced the following average cost per bridge accident: $7,605 for ice and snow, $10,340 for wet, and $17,180 for dry pavements. Using these average bridge accident costs in the first example (Example A) of Appendix H gives a benefit/cost ratio of 1.138, which is 2.39 times as large as the B_s/C value reported. These results serve to illustrate that the economic evaluations must be considered in terms of the accident costs used. The B_s/C value for Example A, based on the data in Table D-4, does not exceed the break-even point, whereas the B_s/C values based on the data in Table D-3 does.

TABLE D-5

AVERAGE BRIDGE ACCIDENT COSTS BY PAVEMENT CONDITION USED IN COST-BENEFIT ANALYSIS EXAMPLES

	Ice and Snow[a/]	Wet	Dry
Cost per accident	$3,180	$4,210	$6,840

a/ The average bridge accident costs for the pavement conditions relating to localized and generalized frost, ice or snow and abrasives on ice are assumed to be the same as that for ice and snow.

APPENDIX E

ROAD SURFACE CONDITION DETERMINATION

The accident rates needed for the benefit model require estimates of the fraction of time (e.g., hours per year) that bridges in the area were exposed to the various pavement conditions. For illustrative purposes, the road surface conditions considered in this report are: ice or snow (subsequently divided into generalized ice or snow and localized ice or snow), wet, and dry. (The road surface condition of abrasives on ice is also considered in the development of the benefit equations; however, no procedure was found satisfactory for estimating the duration of this surface condition. This condition is, therefore, omitted from this discussion.) Estimates of these conditions were obtained from U.S. National Weather Service Local Climatological Data (LCD) reports published monthly by the Environmental Science Service Administration using the procedure outlined as follows. LCD reports are available only from the major weather reporting stations. However, they are more detailed than the reports available from other stations and provide a better basis for evaluating long term weather conditions over a large area. If one were interested in the bridge conditions at a particular time and place (e.g., at the scene of an accident), it might be more desirable to examine whatever weather data are available from the closest weather reporting stations.

The following items available from the LCD reports were used to assess road exposures:

1. Daily precipitation of snow or sleet and total water equivalent.
2. Fairly complete observations of weather and temperature at 3-hr intervals.
3. Hourly precipitation.

To obtain an estimate of the time of snow or ice and wet conditions, these data were evaluated in the following order. The first two items were used to screen time periods of interest; the hourly precipitation provided the final element needed in the estimation procedure. Once the snow or ice and wet conditions were estimated, the dry exposure time was determined by subtraction.

In examining the data, no attempt was made to estimate the time when frost conditions occurred (see Appendix C). This condition is extremely local in nature and microclimatological effects would have to be included. This detailed approach would have required more time and expense than was possible under the budgetary constraints of the program.

The following procedure was followed in estimating the four road surface exposure times. First, a method was developed to permit the use of LCD reports and to also provide a reasonable estimate of what the actual bridge conditions were throughout the year. LCD reports, in and by themselves, can not be expected to yield meaningful bridge surface exposure data because they are not collected from actual highway conditions. Additional information must be used to relate weather conditions to roadway conditions. Second, an empirical method was established to estimate the exposure for both generalized and localized icing conditions.

Data collected in connection with field tests (*3*) of ice and snow detection systems furnished the needed clues to relate weather to roadway conditions. These tests were conducted during the 1970-1971 winter on an Interstate bridge near Iowa City, Iowa. The data used were:

1. Nearby (Cedar Rapids, Iowa) FAA weather reports (similar to LCD reports) containing hourly temperatures and type of precipitation.
2. Results from moisture and ice sensors implanted in the bridge deck.
3. Personal observations by MRI.
4. Iowa State Highway Commission maintenance reports.

These data resulted in the following "best" estimate of exposure to various roadway conditions on the bridge during the test period from 22 November 1970 (the date of the first significant snowfall) until 22 April 1971 (the date when the experiment was officially stopped for lack of further hazardous winter driving conditions); the total time of the experiment was 3,648 hr:

Ice	33 hr
Snow	102 hr
Ice and Snow	135 hr
Wet	465 hr

Using these data, a rule of thumb was constructed for estimating exposure times from the LCD. By trial and error, a method was found that, when applied to the Cedar Rapids FAA weather reports, yielded:

Ice	32 hr
Snow	105 hr
Ice and Snow	137 hr
Wet	463 hr

The developed rule of thumb is as follows:

1. Ice or Snow—Assign an hour of exposure to snow (or ice) for every hour of measurable (greater than a trace amount) snowfall (or freezing rain) recorded. An amount of precipitation smaller than 0.01 in. of water equivalent in an hour is recorded as a trace.

The hourly LCD did not classify the precipitation type, so the daily and 3-hr data had to furnish needed clues. If the daily precipitation record indicated a measurable amount of snow or sleet and if there was no indication of

rain or drizzle during the day, it was assumed that all the precipitation was in the form of ice or snow. In this case the number of hours when ice or snow covered the roads could be easily estimated from the hourly precipitation record. If the observations at 3-hr intervals indicated that rain or drizzle occurred as well as snow or sleet, but at different times, then the number of hours of ice and snow coverage was estimated from the hourly precipitation record but restricted to those hours when snow or sleet was observed. When rain and snow were both observed in the same 3-hr period, the temperature was used to estimate when icy roads would have resulted. On days when there was freezing rain or freezing drizzle, the temperatures and weather at 3-hr intervals were compared with hourly precipitation to determine the number of hours that the roads were icy.

Since the estimated exposure to ice or snow was computed from a rule of thumb based on an actual bridge deck condition, this total estimate includes both generalized and localized icy conditions. The following division of the total hours of exposure to ice or snow is based on observations of bridges before, during, and after periods of hazardous conditions and engineering judgment:

a. Assign three-fourths of the total to generalized conditions.
b. Assign one-fourth of the total to localized conditions.

2. Wet—Assign an hour of exposure to wet for:

   a. Every hour of rainfall (including trace amounts).
   b. Every hour of fog.
   c. Every period of precipitation (rain, snow, or freezing rain) regardless of the duration period.

The rule of thumb for estimating road (bridge) surface exposure times was applied uniformly to the LCD for the various meteorological regions considered in this report. It is true that the procedure was developed using Iowa data that might not apply to other regions. However, until more reliable data have been collected, the procedure appears to yield reasonable engineering estimates of exposure times.

Two more comments can be made in favor of this method. First, the procedure will enable a highway engineer to rapidly assess exposure times using currently available data. The technique is simpler to apply than another one recently proposed (*3*). Second, the rule of thumb indirectly reflects the influence of such variables as the intensity of winter maintenance and the traffic volume. Both of these quantities should rightfully be accounted for in evaluating exposure times in order that the application of the cost-benefit model to the analysis of countermeasures provide realistic results. The estimation of exposure times of ice and snow strictly from weather data (LCD's) will, in general, tend to be more conservative (larger) than might be observed on the Interstate (or highly traveled) System in a region accustomed to ice and snow, thus producing a smaller benefit/cost ratio than is actually possible.

APPENDIX F

COST MODEL

When costs are considered in a comparative analysis, such as a benefit/cost comparison, it is necessary to normalize the costs in time. Conventionally, cost comparisons are made based on present worths or on average annual costs using the standard compound interest formulas. These normalizations allow comparison of initial costs with costs that recur annually or at some discrete intervals.

For the benefit/cost methodology described here, the average annual cost method was used for two reasons. First, having average annual costs is more convenient for the benefit/cost calculations because benefits are computed on an annual basis. And, second, using the annualized cost method yields simpler equations for computing the individual cost elements.

For convenience, in the following presentation of component cost equations, the kinds of costs are categorized according to the activity to which they apply. These categories are:

1. Costs for detection and/or forecast of localized frost and ice.
2. Costs for the active countermeasure agent.
3. Costs for repairs and maintenance to the bridge deck or structure because of deterioration caused by the countermeasure agent.

Many combinations of costs for categories 1 and 2 may be used. For any localized countermeasure system (and set of bridges), the costs that apply from each of these categories depend on the detection and forecast components used, the active countermeasure agents used, the bridge deck characteristics, and the countermeasure systems and agents used for generalized snow and ice conditions.

DETECTION AND FORECAST COSTS

Detection

Use of Existing Patrols

The simplest system, as shown in Figure F-1, makes use of existing highway patrols to report localized ice and frost conditions. This simple system will probably have low de-

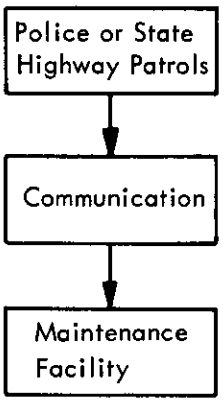

Figure F-1. Detection with existing patrols.

pendability because the patrols have other tasks with higher priorities.

Since these patrols already exist for other purposes, there are only two sources of cost: communications systems and facility operations. Special communication systems exclusively for this purpose cause a capital investment cost, a maintenance cost, and an operation cost. The use of existing communications systems may result in a charge per communication or a *pro rata* share of the items listed earlier. In the maintenance facility, there may be a personnel cost if the facility is manned exclusively or partly for the receipt of communications. The costs may be computed as a sum of the elements given as follows:

1. Communication System (Owned)—

$$\text{Annual Cost} = f_c(C_c[\text{CRF}]_i^{L_c} + E_c) \qquad \text{(F-1)}$$

where:

f_c = fraction of communication system cost charged to localized frost and ice;
C_c = initial cost of communication system, including installation and engineering;
L_c = life of communication system, years;
i = interest rate;
$[\text{CRF}]_i^{L_c}$ = capital recovery factor found in compound interest tables. The algebraic form of this factor is $[i(1+i)^{L_c}]/[(1+i)^{L_c}-1]$; and
E_c = annual maintenance and operating costs of the communication system.

2. Communication System (Leased)—

$$\text{Annual Cost} = f_c K_c \qquad \text{(F-2)}$$

where:

f_c = fraction of communication system charged to localized frost and ice; and
K_c = annual lease rate for communication system.

3. Facility Operations—

$$\text{Annual Cost} = f_w K_w N_w \qquad \text{(F-3)}$$

where:

f_w = fraction of facility watch cost charged to localized frost and ice;
K_w = cost per facility watch; and
N_w = number of facility watches per year.

Use of Exclusive Patrols

Exclusive patrols for bridge surveillance may be made when weather conditions indicate. The patrol may either be capable of undertaking the countermeasure or may need to call for countermeasure units. This distinction is shown in Figure F-2 as a system design decision.

The patrol decision may make use of special meteorological instrumentation (either at the facility or remote), weather service information (federal or private), state police reports, or simply the experience of the local maintenance personnel.

1. Facilty or Remote Meteorological Instrumentation—

$$\text{Annual Cost} = f_i(C_p[\text{CRF}]_i^{L_f} + C_i[\text{CRF}]_i^{L_i} + E_i) \qquad \text{(F-4)}$$

where:

f_i = fraction of instrumentation cost charged to localized frost and ice;
C_p = initial cost for routing power to instrumentation site;
[CRF] = capital recovery factor;
L_f = life of facility, years;
i = interest rate;
C_i = initial cost of the instrumentation system, including installation and engineering;
L_i = life of instrumentation system, years; and
E_i = annual maintenance and operating cost of instrumentation system.

2. Weather Service—If a private weather service is employed, a cost $f_{ws} K_{ws}$ would be incurred each year, where K_{ws} is the annual service rate and f_{ws} is the fraction of the service charged to localized frost and ice.

3. Communications Systems (Instrumentation or Weather Service to Facility)—The cost elements are given by either Eq. F-1 or Eq. F-2.

4. Facility Operations—The cost is given by Eq. F-3.

5. Patrol in Units Without Countermeasure Capability—

$$\text{Annual Cost} = N_p\left[D_p \cdot K_v + K_d\left(\frac{D_p}{V_p} + K_t\right)\right] \qquad \text{(F-5)}$$

where:

N_p = annual number of vehicle patrols for localized frost and ice;
D_p = average distance traveled by patrolling vehicles, miles;
K_v = cost per vehicle mile;
K_d = driver's pay per hour;
V_p = average speed of patrolling vehicles, mph; and
K_t = lost time (hours) per vehicle patrol due to decision waits and to minimum pay period.

The cost per vehicle mile for each type of vehicle is often already available as part of the state accounting data. If not, it can be computed using, for instance,

$$K_v = \frac{L_{vy}}{L_{vm}}\left(C_v[\mathrm{CRF}]_i^{L_{vy}} - S_v[\mathrm{SFF}]_i^{L_{vy}} \right) + K_{vm} \qquad \text{(F-6)}$$

where:

K_v = cost per vehicle mile;
L_{vy} = life of vehicle, years;
L_{vm} = life of vehicle, miles;
C_v = initial cost of vehicle;
[CRF] = capital recovery factor;
i = interest rate;
S_v = salvage value after L_{vy} years and L_{vm} miles; and
[SFF] = sinking fund factor found in compound interest tables. The algebraic form of this factor is $i/[(1+i)^{L_{vy}} - 1]$; and
K_{vm} = operating, maintenance, and repair costs per mile.

6. Communication System (Patrol Vehicle to Facility)—The costs are again given by Eq. F-1 or Eq. F-2. If the same system is used for two or more of the communication needs, the f_c values should reflect fractional charges for specific activities in order to avoid duplicate charges.

7. Patrol in Units with Countermeasure Capability—This cost includes all of the costs of Eq. F-5 plus a "make-ready" cost per patrol vehicle, $N_p K_{mr}$, where N_p is the annual number of vehicle patrols for localized frost and ice and K_{mr} is the make-ready cost per vehicle at the beginning of each patrol and the cleanup costs after patrol. Also, it is expected that the cost per vehicle mile may differ from the value for vehicles without countermeasure capability, since different vehicles may be used. The costs associated with countermeasure equipment and supplies are incorporated in the costing of specific countermeasures, discussed later.

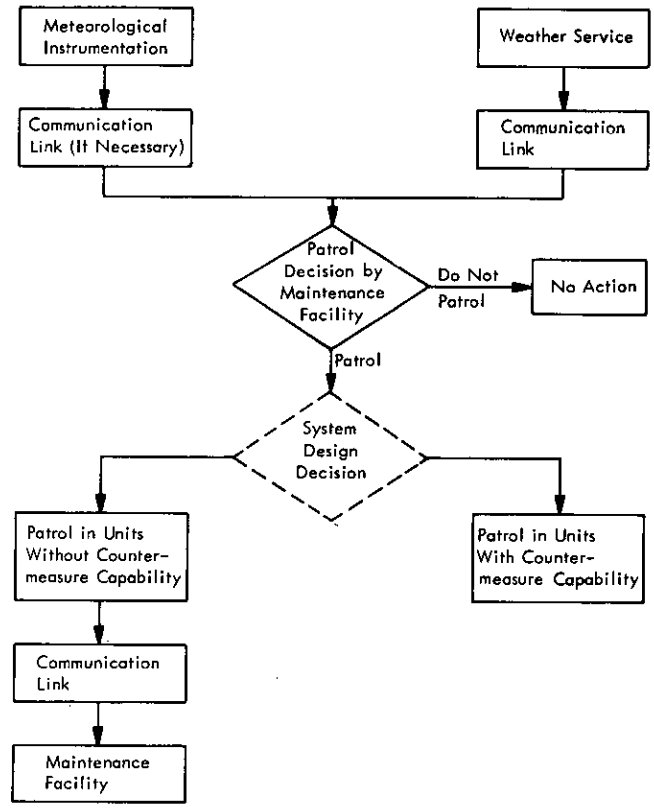

Figure F-2. Detection with specific or special patrols.

Use of Sensor Systems

The most sophisticated system uses bridge sensors and logic circuitry to detect the presence of frost or ice on the bridge deck. The affirmative detection can be signaled to the maintenance facility or can be used to actuate automatic countermeasures. The flow diagram is shown in Figure F-3.

1. Bridge Sensors (Installed in Pavement)—For sensors that can be salvaged when the bridge deck is resurfaced or replaced, the cost is given by:

$$\text{Annual Cost} = C_{es}[\mathrm{CRF}]_i^{L_f} + C_{ps}[\mathrm{CRF}]_i^{L_{ps}} + E_{ps} \qquad \text{(F-7)}$$

where:

C_{es} = initial engineering cost associated with design;
[CRF] = capital recovery factor;
i = interest rate;
L_f = life of facility, years;
C_{ps} = initial cost of pavement sensors including installation;
L_{ps} = life of pavement sensors, years; and
E_{ps} = annual maintenance and operating costs of the sensors.

For pavement sensors that can not be salvaged when the deck is resurfaced, the cost of the sensors will be incurred each time the sensor is replaced and each time the pavement is resurfaced. To precisely account for these events, a very complex equation is needed to account for the varied sequences of costs. To simplify this equation, an approximation was found that has only a 5 percent error for the "nominal worst case." (The "nominal worst case" considered was a 10-year pavement life and a 3-year sensor life.) Actually, the benefit-cost analysis is even less sensitive to this error because sensor costs are added to the larger logic circuitry costs.

The following equation shows the modification of Eq. F-7 to approximate the additional sensor cost due to replacement at the time of resurfacing:

$$\text{Annual Cost} = C_{es}[\mathrm{CRF}]_i^{L_f} + C_{ps}([\mathrm{CRF}]_i^{L_{ps}} + i) + E_{ps}$$

2. Logic Circuitry—The cost is given by:

$$\text{Annual Cost} = (C_w + C_{el} + f_p C_p)[\mathrm{CRF}]_i^{L_f} + C_l[\mathrm{CRF}]_i^{L_l} + E_l \qquad \text{(F-8)}$$

where:

C_w = initial cost for wiring and housing;
C_{el} = initial engineering cost associated with design;
f_p = fraction of power access cost charged to localized frost and ice;
C_p = initial cost for routing power to the site;
[CRF] = capital recovery factor;
i = interest rate;
L_f = life of facility, years;

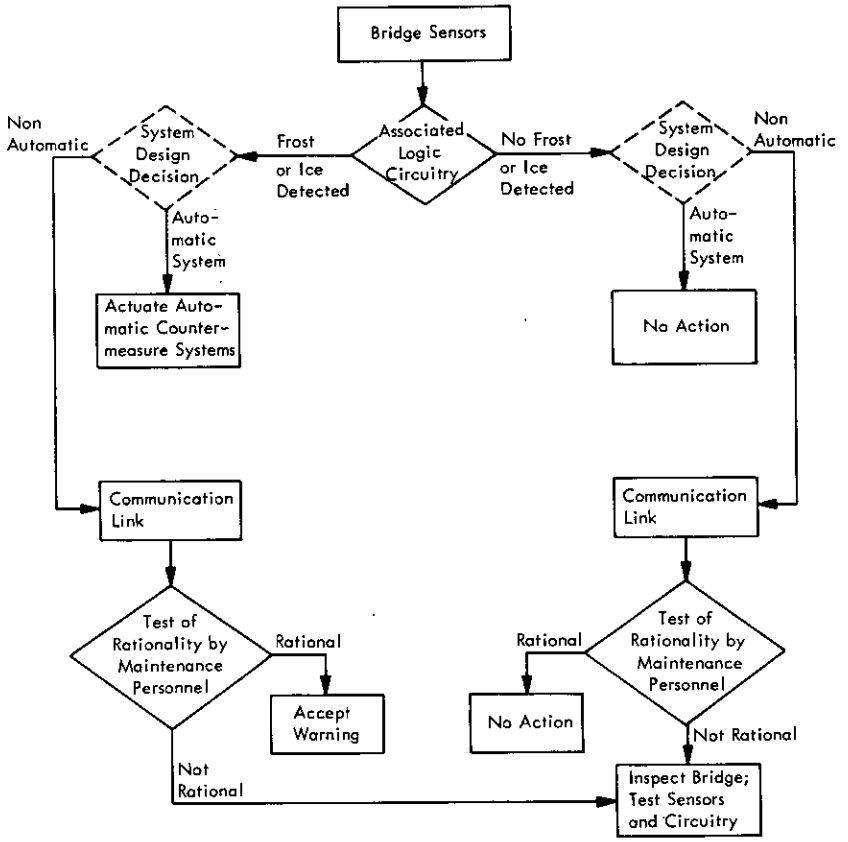

Figure F-3. System with frost and ice detector.

C_l = initial cost of logic circuitry including installation (not including the cost C_w);
L_l = life of logic circuitry, years; and
E_l = annual maintenance and operating cost for the logic circuitry. (This term may be included with E_{ps} in Eq. F-7.)

3. Communication System—The communication system cost is again given by Eq. F-1 or Eq. F-2.

Forecast

There may be some element of forecasting in the systems for detection. For instance, the decision to undertake specific surveillance patrols is probably based on a forecast of enhanced probability of frost or ice formation. When the main emphasis is on forecasting, however, the intent is usually to apply countermeasures before the hazardous condition occurs.

The forecast system diagrammed in Figure F-4 is very similar to the patrol decision model in Figure F-2. The elements in this forecast system duplicate those in the detection system of Figure F-2, and the cost itemization has the same form.

The sophisticated forecasting system shown in Figure F-5 is the counterpart of the detection system in Figure F-3. The elements in this forecast system duplicate those in the detection system of Figure F-3, and the cost itemization is the same.

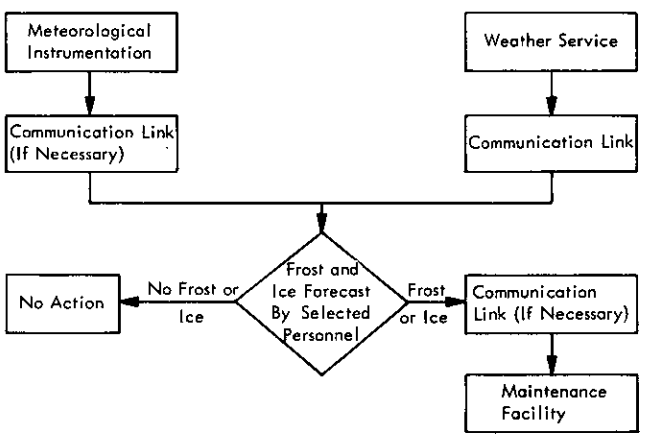

Figure F-4. Forecast by selected personnel using available data.

COUNTERMEASURES

The yearly costs for a variety of countermeasures are given in the following paragraphs.

Fixed Signing

Note in the following that maintenance cost is deleted because it is insignificant.

$$\text{Annual Cost} = C_{ef}[\text{CRF}]_i^{L_f} + C_{fs}[\text{CRF}]_i^{L_{fs}} \qquad \text{(F-9)}$$

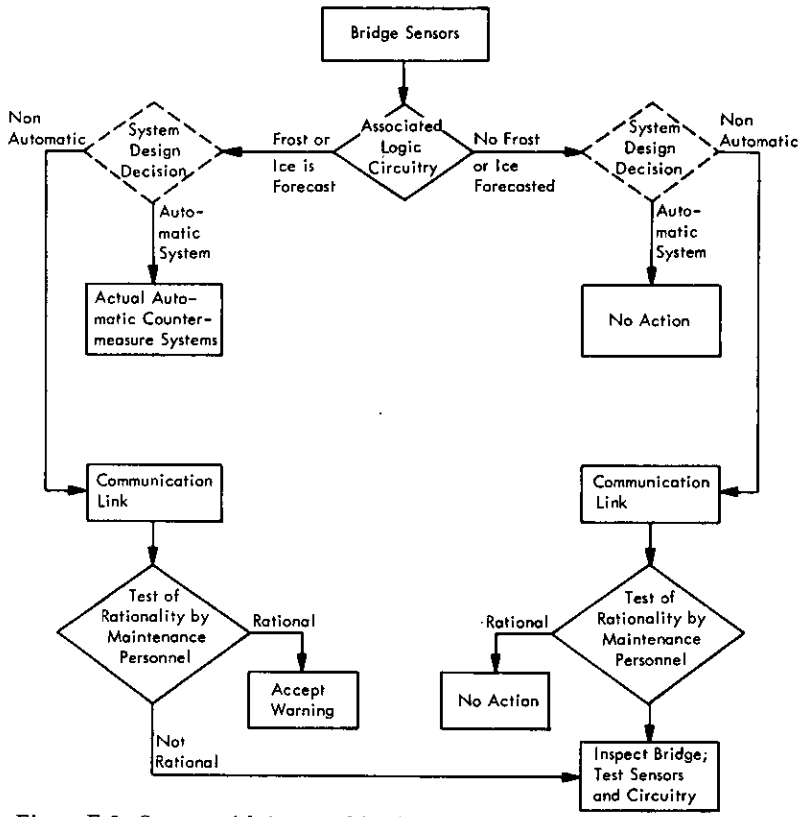

Figure F-5. System with frost and ice forecaster.

where:

C_{ef} = initial engineering cost associated with sign installation;
[CRF] = capital recovery factor;
L_f = life of facility, years;
i = interest rate;
C_{fs} = initial cost of the fixed sign including installation; and
L_{fs} = life of fixed sign, years.

Optional Display Signing

Note that this type of signing can be turned on and off.

$$\text{Annual Cost} = (f_p\, C_p + C_{ed})[\text{CRF}]_i^{L_f} + C_d[\text{CRF}]_i^{L_d} + Ed \qquad \text{(F-10)}$$

where:

f_p = fraction of power access cost charged to localized frost and ice;
C_p = initial cost for routing power to the site;
C_{ed} = initial engineering cost associated with design and installation;
[CRF] = capital recovery factor;
i = interest rate;
L_f = life of facilty, years;
C_d = initial cost for the optional display sign including installation;
L_d = life of optional display sign, years; and
E_d = annual maintenance and operating costs for the optional display sign.

Heated Pavement on Bridge Deck

Let:

f_h = fraction of pavement heating cost charged to localized frost and ice;
C_{ho} = initial wiring cost associated with heated pavement operation;
Y_p = remaining normal life of pavement component at time of initial heating installation, years;
L_p = life of the pavement component with the heating system, years;
L_{pn} = normal life of pavement component, years;
L_h = life of heating component, years;
C_{pn} = normal cost of replacing pavement component;
C_p = initial cost of routing power to the site;
C_{eh} = initial engineering costs associated with the installation;
[CRF] = capital recovery factor;
i = interest rate;
L_f = life of facility, years;
C_h = purchase and installation costs of heating system (costs in excess of reconstruction or repaving without heating); and
E_h = annual maintenance and operating costs of the heating system.

The annual cost depends in part on the relative lives of the heating elements and the pavement component in which

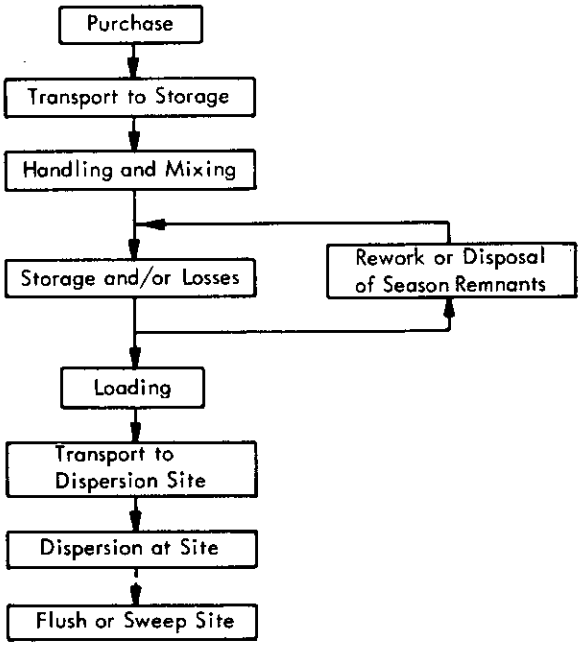

Figure F-6. Deicing materials activities.

they are contained. For $L_h \geq L_p$, the pavement life dictates replacement frequency and the annual cost is given by:

$$\text{Annual Cost} = f_h\left[\left(C_{ho} + \frac{[Y_p + L_p - L_{pn}]C_{pn}}{L_{pn}} + C_p + C_{eh}\right)[\text{CRF}]_i^{L_f} + \left(C_h + \frac{[L_{pn} - L_p]C_{pn}}{L_{pn}}\right)[\text{CRF}]_i^{L_p} + E_h\right] \quad \text{(F-11)}$$

For $L_h < L_p$ the life of the heating element is shortest and dictates the replacement schedule for both pavement component and element. The schedule of costs is given by:

$$\text{Annual Cost} = f_h\left[\left(C_{ho} + \frac{[Y_p + L_h - L_{pn}]C_{pn}}{L_{pn}} + C_p + C_{eh}\right)[\text{CRF}]_i^{L_f} + \left(C_h + \frac{[L_{pn} - L_h]C_{pn}}{L_{pn}}\right)[\text{CRF}]_i^{L_h} + E_h\right] \quad \text{(F-12)}$$

The foregoing equations include two compensations for the effect of the countermeasure system on pavement costs. The term $[f_h(Y_p + L_p + L_{pn})C_{pn}]/L_{pn}$ charges the countermeasure system with the value of the unused life of the pavement component discarded in order to install the heating system. The term $f_h C_{pn}[(L_{pn} - L_p)/L_{pn}]$ charges the system with the decrease in the life of the pavement component due to the presence of the heating system. However, if the heating system is beneficial to the pavement life, the term may be negative, indicating a cost savings over unheated pavement. The term $f_h C_{pn}[(L_{pn} - L_h)/L_{pn}]$ includes the compensation described previously and also a cost against the system for discarding useful pavement life in order to replace the short-lived heating elements. It also may be positive or negative.

The pavement costs charged against the system are approximate in the form shown. A more accurate account would be based on discounted worths. However, the proportionalities employed will provide satisfactory results if the replacement intervals are not drastically different from the normal life of the pavement component.

If the means of heating are not buried in the paving, the schedule of system replacements is independent of the pavement schedule, and the annual costs are computed by either Eq. F-11 or Eq. F-12 excluding the term, Y_p. The $(L_{pn} - L_p)/L_{pn}$ term is retained because the heating may have an influence on pavement life.

Deicing Chemicals and/or Abrasives

The sequence of events for the deicing materials is diagrammed in Figure F-6 to identify the origins of costs.

The annual cost chargeable to localized frost and ice to purchase, to prepare, and to store the materials can be calculated with the following definitions:

f_m = fraction of materials used for localized frost and ice;
W_m = weight of materials used annually, tons;
K_{sc} = cost per ton for salt;
P_{sc} = proportion of salt in material mix;
K_{cc} = cost per ton for calcium chloride;
P_{cc} = proportion of calcium chloride in material mix;
K_{ac} = cost per ton for abrasives; and
P_{ac} = proportion of abrasives in material mix.

The annual cost to prepare and store materials is small compared to the purchase price, probably less than 10 percent. Therefore, the total annual costs can be reasonably estimated by multiplying the purchase cost by 1.05:

$$\text{Annual Cost} = 1.05\, f_m W_m (K_{sc} P_{sc} + K_{cc} P_{cc} + K_{ac} P_{ac}) \quad \text{(F-13)}$$

Next, the costs to load are itemized, as well as the costs to transport to dispersion sites and to disperse. The cost depends on whether the dispersing vehicles also have a patrol function. The cost items involved are as follows:

N_d = annual number of dispersion trips for localized frost and ice;
K_{mr} = make-ready cost per vehicle at the beginning of each dispersion trip and the cleanup costs after patrol;
D_d = average round-trip distance of dispersion vehicle, miles;
K_v = operating cost per vehicle-mile of dispersion vehicle;
K_d = driver's pay per hour; and
V_d = average dispersion vehicle speed, mph.

The major additional annual costs in a system that does *not* patrol in dispersing vehicles are

$$\text{Annual Cost} = N_d\left[K_{mr} + D_d\left(K_v + \frac{K_d}{V_d}\right)\right] \quad \text{(F-14)}$$

For systems in which patrols are made in vehicles with dispersing capability, the costs of the make-ready and patrol have been included under detection and forecast. Because the actual dispersion takes very little time at each site, the costs associated with the dispersing activity are negligible.

The last item in Figure F-6, "Flush or Sweep Site," is optional and might be more properly considered as a maintenance activity necessitated by countermeasure effects (see next section). In any case, the yearly cost of this activity chargeable to localized frost and ice can be readily determined. For example, Eq. F-14 for the costs to load, transport, and disperse deicing materials may be used by simply reinterpreting some of the cost items. The quantity N_d, for example, would be the number of flush or sweep trips per year necessitated by treatment of localized frost and ice. (It may be a prorated share of the total of such trips.)

COST OF REPAIR AND MAINTENANCE NECESSITATED BY COUNTERMEASURE EFFECTS

The countermeasure effects and associated costs are examined for the principal countermeasure types. In some cases, no data are available from well-controlled tests to identify the effects of the countermeasure. In other cases, the effect may be known; but good, quantitative data are lacking or are complicated by the influence of several properties of the construction materials and processes.

The reader may at this point be reminded that bridge superstructures can also be damaged in accidents and require repair. These repair costs properly belong under accident costs and will not be itemized in this section.

Signs

The maintenance costs for the signs have been included in the costs for the countermeasure.

Heated Pavements or Bridges

The countermeasure costs in this case included an account of the effects on the pavement life, which appear to be the most significant cost consideration. The effect can be beneficial or detrimental. One would anticipate that the elimination of some freezing cycles would be beneficial, especially when the eliminated cycles normally occur with a wet surface. In contrast, thermal stresses could be increased and reinforcement corrosion could be accelerated. There are very few data to evaluate these possibilities.

Deicing Chemicals

Bridge deck deterioration has become a major problem for most highway departments in the last decade. Many people close to the problem have singled out deicing chemicals as the principal contributor. But the recent acceleration of bridge deck deterioration is also highly related to a combination of other factors, such as increased wheel loads, higher traffic volumes and speeds, greatly increased number of bridges since the advent of the Interstate System, more flexible bridges, more bridges each year approaching an age of deterioration, and previous lack of knowledge on construction quality factors contributing to scaling and spalling.

Deicing chemicals are definitely detrimental to portland cement concrete and increase maintenance and repair costs. Although the bridge deck deterioration problem has been investigated and reported extensively, the quantification of the extra repair and maintenance costs associated with deicing chemicals is not well documented.

Both scaling and spalling are accelerated by conventional deicer chemicals; however, both occur without deicers. Scaling (with or without deicers) is retarded by concretes which (1) contain 4 to 7 percent entrained air, (2) were mixed with low water/cement ratios, (3) were finished to preserve the entrained air near the surface, and (4) were well cured and partially dried before exposure to freezing cycles.

Laboratory tests show that scaling occurs most rapidly when the surface is covered by water (or salt solutions) during a freeze. Scaling also correlates with salt solution strength, with weak and intermediate solutions producing the most accelerated scaling. These factors indicate that the scaling penalty associated with deicers will depend on temperature and precipitation cycles together with the actual drainage characteristics of the deck and its concrete properties.

As a consequence of the many complicating factors indicated, the additional maintenance and repair costs for scaling attributable to deicers are modeled based on the difference between (1) the inherent resistance of the portland cement concrete deck to scale as indicated by the number of years until resurfacing (or surface repair) is required without deicer application, and (2) the lowered resistance when deicers are applied as indicated by the reduction in years to resurfacing (or surface) repairs.

In addition, it is assumed that on decks where deicers are employed for both general snow and ice and localized frost and ice, the scale acceleration due to the localized phenomena is proportional to the fraction of deicers used for that purpose. It should also be noted that surface repair can include repair to other portland cement concrete surfaces, such as walks and railings.

The same general approach will be used in considering accelerated spalling due to deicer application. (Spalling also occurs without deicers.) The most frequent origins of spalling are the transverse reinforcing bars. Resistance to spalling (with or without deicers) is enhanced by low shrinkage concrete with low water/cement ratios, by adequate concrete cover over the reinforcing, and by structural stiffness to minimize cracking in the deck.

Salts are carried into the concrete in solution. To some extent, they may then react with the hydrolyzed cement compounds. Salts that enter the mortar at the reinforcing accelerate corrosion by two mechanisms. They reduce or eliminate the chemical passivity of the cement compounds, and they provide lowered electrical impedances through the concrete. Upon forming, the corrosion compounds exert pressure against adjacent concrete, which may produce a spall or loose surface layer.

To develop a precise cost model for bridge deck deterioration is a very exhaustive task because of the many factors affecting deterioration and their complex interaction with maintenance processes. Also, a completely compre-

hensive model would have many parameters that can not be quantified at this time. Therefore, this project developed a generalized model that is consistent with the state of the art. This model considers the costs and effective lives of several general categories of preventive and repair measures for bridge deck spalling and scaling.

The maintenance cost model for bridge deck deterioration resulting from deicing chemicals used for localized ice and frost is shown as follows. Only those parts of the model applicable to a particular situation are considered in each calculation.

$$\text{Annual Cost} = f_p A \Bigg\{ [\text{CRF}]_i^{L_f} \Bigg[\sum_{a=1}^{q} (U_o[\text{PWF}]_i^{aL_{od}} + U_s[\text{PWF}]_i^{2aL_{od}}) - \sum_{b=1}^{r} (U_o[PWF]_i^{bL_{oo}} + U_s[PWF]_i^{2bL_{oo}}) + U_l \Bigg(\sum_{c=1}^{s} [\text{PWF}]_i^{cL_{ld}} - \sum_{d=1}^{t} [PWF]_i^{dL_{lo}} \Bigg) \Bigg] + U_p \Bigg[\frac{A_{sd} - A_{so}}{A} \Bigg] \Bigg\} \qquad \text{(F-15)}$$

where:

$a, b, c, d,$ = index numbers with the limits of q, r, s, and t, respectively. The limits are determined as follows: if L_{xx} = life of maintenance element, j = the limit number, and α = coefficient of the life in the equation (either 1 or 2), then j is determined such that $\alpha j L_{xx} < L_f$ (in other words, each element life is cycled as many times as it can be without going beyond the life of the bridge deck);

f_p = fraction of total maintenance and repair costs charged to localized frost and ice;

A = area of the bridge deck, square feet;

[CRF] = capital recovery factor;

L_f = remaining life of the bridge deck, years;

U_o = unit cost of asphalt overlay, dollars per square foot;

U_s = unit cost of permanent seal, dollars per square foot;

U_l = unit cost of linseed oil seal, dollars per square foot;

U_p = unit cost to patch spall damage, dollars per square foot;

[PWF] = present worth factor, present worth of a future sum, $1/(1+i)^n$;

L_{od} = life of an asphalt overlay with deicers in use, years;

L_{ld} = life of a linseed oil seal with deicers in use, years;

L_{oo} = life of asphalt overlay without deicers in use, years;

L_{lo} = life of linseed oil seal without deicers in use, years;

A_{sd} = average annual area of spall damage with deicers in use, square feet; and

A_{so} = average annual area of spall damage without deicers in use, square feet.

APPENDIX G

COST ESTIMATES

The cost and other estimates given in this appendix were obtained primarily from published literature and should be considered representative averages. State highway departments applying the model will, in all likelihood, have data that reflect regional, maintenance policy, climatic, and other effects.

LABOR

Labor cost estimates for Minnesota (*31*) are as follows:

Classification	*Average Monthly Salary (Dollars)*
Highway Maintenance Man I	590
Highway Maintenance Man II	663
Highway District Foreman	926
Laborer I	523
Laborer II	590
Heavy Equipment Operator	826
Highway Maintenance Foreman II	860

These figures were obtained from 1965 averages projected to 1969 using the cost indices included in Ref. (*31*). The salary figures include fringe benefits (vacation, sick leave, overtime pay, etc.). The duties of the various classifications are not defined, but they can be surmised.

For comparison with the preceding figures, the average salary (with fringe benefits) is about $4/hr for snow and ice removal equipment operators in Pennsylvania (*32*).

A clue to regional variation in labor costs is given in Ref. (*33*) (p. 79, Table 22). These data imply that labor costs are highest in the Far West, lowest in the Southeast, and approximately uniform throughout the remainder of the U.S.

CHEMICALS AND ABRASIVES

Approximate prices for deicing chemicals (*4*) are:

Material	*Price ($/Ton)*
Sodium Chloride	10-20

Calcium Chloride	30-35
Urea	90
Calcium Formate	70-90
Formamide	200

The cost of chemicals varies considerably, depending on geographical location, distance from the source, and method of shipping. Additional data on sodium chloride and calcium chloride costs (*34*) are:

	*Cost per Ton (Dollars)**	
State	*Sodium Chloride*	*Calcium Chloride*
Arkansas	19.50	51.20
Connecticut	13.00	35.00
Kansas	8.28	58.25
Michigan	5.40	26.00
Missouri	15.00	50.00
Montana	21.00	68.00
Nebraska	13.00-14.00	50.00-60.00
New Hampshire	14.00	-
New Jersey	12.00	42.00
North Dakota	21.00	62.20
Texas	18.36	-
Washington	16.00	36.00
Pennsylvania Turnpike	13.00	38.00
Richmond-Petersburg Turnpike	15.60	38.00

* It is not stated whether the cost for calcium chloride is for pellet or flake form.

The cost of abrasives is substantially less than the cost of chemicals. For example, Ref. (*35*) states that abrasive costs in one New York State Maintenance District are about one-sixth that of sodium chloride.

EQUIPMENT

Ice and frost patrols may be conducted in vehicles with or without chemical and/or abrasive dispensing capability. For vehicles with dispensing capability, the estimated operating cost per mile is $0.10 (*32, 36*). For vehicles without dispensing capability (assumed to be of the pickup class) an estimated operating cost of $0.06 per mile is obtained from Ref. (*33*), p. 80, Table 25.

Another kind of salt spreading equipment is one mounted directly on a bridge railing or structure and dispenses salt only over a limited portion of the deck surface. The Hinricks Deicer System was designed primarily to be used with this kind of automatically activated salt spreading equipment. The manufacturer recommends that the salt spreading units be positioned at 100-ft intervals. The fixed salt spreading installation in Bismarck, N. Dak., is the only one known to exist at the present time. Problems have developed with these spreading units wherein the salt became caked and would not spread properly. The cost of each spreading unit has not been established at this time, but it is reported to be between $300 and $500.

PAVEMENT AND BRIDGE DECK HEATING SYSTEMS

A variety of pavement heating systems can be employed. Some of these are as follows:

1. Electrical resistance—embedded cable, embedded wire mesh, and conductive pavement.
2. Embedded pipe with circulating fluid—low temperature fluid and high temperature fluid or steam.
3. Overhead radiant heaters.
4. Heating enclosed space under bridge deck.

The installation costs of the electrical systems are all similar, averaging about $4/sq ft of pavement (*34*). Operating costs vary considerably with climatic conditions and are very difficult to evaluate. For rough estimating, however, an installation (embedded wire mesh) in Toronto was reported to have an average annual operating cost of $0.32/sq ft (*37*). The annual operating costs for experimental installations (embedded electrical cable) in Trenton, N.J., averaged $0.45/sq ft (*38*).

Installation costs for embedded pipe systems average about $4/sq ft, comparable to equivalent electrical systems. Operating costs are somewhat lower. For instance, a system on the ramps of the John F. Fitzgerald Expressway (Boston) has an average operating cost of $0.133/sq ft. Other special systems have lower costs. One in Klamath Falls, Ore., which uses a natural supply of hot mineral water, was installed in 1949 at a cost of $0.87/sq ft. During the period 1959 to 1962 the average annual operating cost was $0.028/sq ft. Another experimental system in Trenton, N.J., uses the earth as a source of heat. Costs are not given, but the operating cost is implied to be about one-hundredth that of melting the snow electrically (*34*).

Overhead radiant heaters have not been employed on ramps or bridge decks. However, estimated installation costs for gas-fired units range from $5.28 to $11.73/ sq ft (*34*). Estimated operating costs are not available.

Heating an enclosed volume below the bridge deck has been investigated experimentally (*9*). The installation cost for a "T" structure (enclosed with urethane foam) was $3/sq ft; for box girder construction the installation cost was $2.25/sq ft. Operational cost was $0.03/sq ft/month for 6 months. (The operational cost is based on actual cost of heating electrically; gas heat is expected to be less expensive.)

These operating costs for the various heating systems suffer from the fact that they were determined in various regions of the country under correspondingly varied climatic conditions. The operating costs for heating an enclosed volume below the bridge deck refer to the localized frost or ice condition (*9*). The other operating costs are for total ice and snow control. These costs, therefore, must be recognized as rough working estimates only.

The cost model, as formulated, includes account of the maintenance costs for the heating systems. To date, however, these systems have been employed on a small scale over comparatively short periods of time, and maintenance cost estimates are not available.

BRIDGE DECK MAINTENANCE

Bridge deck maintenance assumes a variety of forms. Activities include patching PCC decks and AC wearing surfaces, installing or patching waterproofing costs, deck slab replacement, etc. The following associated cost estimates have been compiled:

	Per Sq Ft
Installation of single coat epoxy seal (*9*)	$ 0.60
Patching single coat epoxy seal (*9*)	0.80
Installation of double coat epoxy seal (*9*)	1.10
Patching double coat epoxy seal (*9*)	0.80
Installation of epoxy seal with AC cover (*9*)	0.75
Application of 1-in. AC cover (*9*)	0.10
Linseed oil treatment (*11*)	0.03
Replacement of PCC deck slab (*9*)*	16.00
Replacement of PCC deck slab (*34*)**	6.35 (average)
Patching PCC deck (*34*)	4.25 (average)
Patching bridge deck holes up to 2-in. deep with:	
Coal tar epoxy resin (*39*)	8.50
Nonshrinking concrete (*39*)	8.50
½ in. bituminous concrete overlay (*40*)	0.04-0.065

* Average cost for five bridge deck replacements, including detours, reported by the California Division of Highways.
** Average cost from seven reconstruction projects reported by New Hampshire Department of Public Works and Highways.

SIGNING

Very limited information is available on cost of signing. A study conducted in Virginia during 1953-1954 showed the labor and material costs associated with manufacturing and erecting 63,500 fixed signs to average $9.80/sign (*41*). This figure does not include maintenance or repair costs.

COMMUNICATION SYSTEMS

Basically, two kinds of communication systems are available for transmitting a warning signal from an ice and snow detection device to a local or central maintenance location. These are radio communications and leased or public telephone lines. The transmission between the device's logic circuit and a nearby warning sign can be accomplished by either direct wire(s) or by radio equipment. The latter case can be considered a part of radio transmission to a central location because the radio equipment needs for transmission to either a warning sign or a central unit are similar.

A comparison of the equipment needs and estimated costs associated with transmissions by both communications systems is given in Ref. (*4*) for both urban and rural areas. For example, the cost of a communication system to transmit a warning signal from one detection device to a station 50 miles away, for one winter season, would be approximately $3,850 for a radio system as compared to $1,260 for a leased telephone system. The cost of the radio communication system is based on the Motorola Alarm Reporting System (MARS). Similar radio equipment is probably available from other manufacturers, such as General Electric, RCA, Sylvania, etc. The cost of a radio system does not include estimates of installation or maintenance. The cost of a leased telephone system, however, includes installation cost and assumes a 4-month rental period for a rural area. The cost differential between telephone and radio becomes more substantial as the number of remote stations (detection locations) increases. However, the radio system becomes more attractive over a longer time period. In the preceding example, the radio system is the cheaper for a 4-year period.

The foregoing costs are presented for illustrative purposes only; the exact cost of a communication system can only be determined once the specific configuration is selected. The cost of a radio system could be reduced by about 60 percent if the warning signal were transmitted over an existing maintenance radio network.

BRIDGE DECK SENSORS AND ASSOCIATED LOGIC CIRCUITRY

The purchase price for ice, snow, and frost detection devices varies considerably, depending on the complexity and sophistication of the logic. Typical purchase prices for the six common devices (*3*) are:

Device	*Cost (Dollars)*
Nelson (road ice detector)	~550
Icelert (road ice and salinity detector; price exclusive of an outdoor enclosure and U.S. freight costs)	640
Econolite (ice moisture detector)	695
CyTronics (ice, snow, and frost detector)	~1,000
Holley (highway ice condition detection system)	2,200
Hinrichs (deicer system—without salt spreaders)	2,900

These costs include all sensors, wiring, and electronics (logic circuitry), but they do not include installation costs. The costs of the bridge deck sensors (those implanted in the roadway and exposed to traffic) generally are not itemized separately. The cost of the two Holley roadway sensors is $550, which is one-quarter of the device purchase price. It is reasonable to assume that this fraction also applies to the other devices except Hinrichs, which does not have any sensors exposed directly to traffic.

Installation and maintenance costs associated with these devices are not available from any published source. However, estimates are available from MRI experience of installing and field testing the six devices under FHWA Contract No. FH-11-7428. Between 2 and 3 man-days effort were required to completely install and check out one device. This includes installing the various sensors, running sensor lead wires to a logic unit located alongside or beneath the bridge deck, and finally checking the unit for response to imposed conditions. Preventive maintenance should be performed on a regular basis after installation. This may require about ½ to ¾-day effort per month per device.

SUPPLY ELECTRICAL POWER TO BRIDGE SITE

The cost of supplying electrical power to a specific bridge site is extremely variable. The cost depends primarily on the availability of an existing power supply. If power is already available at the bridge, the cost of an electrical

hookup is nominal, say, in the order of $50 to $75. However, if a power line has to be brought to the bridge from some distance away, the costs could run several thousand dollars. (The Iowa State Highway Commission reported that it would cost about $3,000 to $4,000 to provide power at one of their bridges which was removed about 1 to 2 miles from an existing power source.) This latter cost would be typical for Interstate bridges located in rural areas.

FRACTION OF COST ITEMS CHARGEABLE TO LOCALIZED FROST AND ICE CONTROL

These parameters are the "*f*" multipliers, which appear throughout the model. Their numerical value must be determined by judgment on the part of the model user. As noted earlier, if a minimum warrant for a countermeasure is being sought, a zero value may be appropriate in application to equipment or services already available for essential purposes. On the other hand, in some areas in California, localized frost or icing occurs exclusively (no general ice and snow occurrences), and the entire cost must be charged ($f = 1$). These two cases are extremes, however. On the average, a value for the *f*'s of 0.1 to 0.25 is probably appropriate; however, judgment should always be used in selecting values, particularly if any local data are available on the relative occurrence of localized frost or ice.

BRIDGE PAVEMENT LIFE (WITH AND WITHOUT EFFECTS OF DEICING CHEMICALS AND PAVEMENT HEATING)

Ideally, one would like to know the schedule of pavement maintenance activities required during the lifetime of a bridge structure. In the present study, the information for three situations would be useful:

1. No use of deicing chemicals or pavement heating.
2. Use of deicing chemicals.
3. Use of pavement heating.

These schedules are impossible to forecast, however, because too much depends on traffic, weather, workmanship, materials incorporated in the initial installations, and subsequent maintenance procedures.

Some very rough guidance information is available. Better information may be available in state highway department maintenance records; this is an avenue that needs exploring.

A good PCC bridge deck might be expected to last from 25 to 30 years years before requiring resurfacing, and a bituminous concrete pavement about 17 years (*42, 43*). These can be taken as a "lives unaffected by ice and snow control procedures," because the references date back to the time when large-scale use of deicing chemicals was just beginning. On the other hand, it is suggested that a concrete bridge deck unprotected from the effects of deicing chemicals would likely require complete replacement at the end of 20 years (*9*). Not much is known about the effect of pavement heating except that high temperature gradients associated with widely spaced embedded cables are known to cause deterioration, whereas low temperatures (as with wire mesh installations) apparently do not (*38*).

The life of the bridge deck can be extended to approximately 50 years despite the use of deicing chemicals (*9*) by:

1. Coating with a single layer of epoxy and patching one-fourth of the surface every 5 years.
2. Coating with a layer of epoxy and a 1½ in. cover of asphaltic concrete (AC); overlaying with 1-in. AC at 16 years and replacing the original cover completely at 32 years.

Other sealant and AC combinations are also mentioned, similar to the one cited.

Linseed oil treatment (*11*) is also widely accepted as an economical and effective (but unquantified) counteractant for the deicing chemical effects. It should be noted that considerations in Ref. (*11*) are for a snow-free, frost-prone region, and techniques are considered that will provide a 50-year structure life.

Thin and light resurface coatings will have expected lives of 7 to 10 years with 5,000 to 7,000 vehicles per day and 4 to 5 years with 50,000-60,000 vehicles per day (*42*). No comment is made about how many times a deck can be resurfaced. If the old surface is removed each time to avoid a dead-weight increase, the number of permissible resurfacings would depend on their effectiveness in protecting the concrete slab.

The estimated life of a ½-in. bituminous overlay (say, to repair scale damage) is 4 to 6 years (*40*).

The preceding data and observations were obtained from a variety of sources. Painstaking examination of state highway department maintenance records and field observations could produce additional data reflecting local effects. Generally speaking, the life of bridge decks and of various protective and restorative constructions is strongly dependent on climate, local maintenance policy, and quality of workmanship, and can be only roughly estimated at best.

BRIDGE SENSOR AND LOGIC CIRCUITRY SERVICE LIFE

Currently, no published data exist on the service life of bridge deck sensors or on the life expectancy of the entire ice and snow detection and warning system. The devices have not been used in the field long enough for an accurate estimate. (It appears that three consecutive winters' testing is about the longest use of any one of the devices.) The device manufacturers suggest that the equipment (including sensors) should have a useful life of between 5 and 10 years provided the equipment is properly maintained and periodically inspected.

DISCOUNT RATE

Discount rates in the range of 5 to 6 percent are probably appropriate. (A rate of 5 percent is used in the cost effectiveness study in Ref. (*9*).)

LOCALIZED FROST AND ICE PATROLS

Number Per Year

This parameter is climate related and must be evaluated using local field experience and judgment. Maintenance field personnel should have an intuitive feel in this regard, and data may be available in some instances from maintenance foremen's logs.

Range and Average Speed

These quantities will vary with local maintenance policy. However, reasonable average working values are:

Range (vehicles with countermeasure capability)—20 lane-miles.
Range (vehicles without countermeasure capability)—20 to 25 road-miles.
Patrolling speed—35 mph average.

Number of Bridges Per Route

This quantity will be readily available from design drawings of the highway section(s) being analyzed.

Lost Time

This parameter must also be evaluated using local field experience and judgment.

NUMBER OF FACILITY WATCHES PER YEAR

See comments in the earlier paragraph related to number of patrols per year.

SERVICE LIFE OF SIGNING

Very little information is available on this subject. From a sample of 3,537 fixed signs (of all sorts), it was determined that the average life per sign was 34 months (*41*). Data have not been found for optional display signs.

COMMUNICATION SYSTEM SERVICE LIFE

Currently, no published data exist on the service life of the various types of communication systems adaptable to ice and snow detection devices. The systems presently in use have not been in the field long enough for an accurate estimate. It is unlikely that such costs will be written off at the end of the first year of use. However, the equipment should have a useful life of about 10 years provided the equipment is properly maintained and periodically inspected.

APPENDIX H

EXAMPLES OF COST-BENEFIT METHODOLOGY APPLICATION

FIRST ILLUSTRATIVE EXAMPLE

The first example consists of installing frost and ice detectors on a group of bridges with like characteristics—ones which are considered important in some sense. (A system is hypothesized which costs $1,000 (sensors plus logic); this is a reasonable price considering currently available systems, although none has been proven effective with frost.) The detectors will then activate motorist warning signs. No other specialized countermeasures, such as maintenance alerting, will be included.

Two sets of bridges will be considered—40 pairs of twin Interstate bridges in the central portion of Iowa, encompassing Des Moines, and a group of 27 bridges which have had accident experience in the northeastern portion of Ohio, including Youngstown.

In each instance a 10-year system life is assumed. A 6 percent interest rate is used in computing the capital recovery factors.

Iowa Interstate Bridges (Example A)

Costs

1. Bridge Sensors (Eq. F-7)—

Annual Cost $C_{es}[\mathrm{CRF}]_i^{L_f} + C_{ps}[\mathrm{CRF}]_i^{L_{ps}} + E_{ps}$

where:

E_{ps} = included with E_l (see under following item 2);
C_{ps} = $250 for the bridge sensors plus 15 man-hours at $4/hr (see also C_l under item 2) = $310 total;
L_{ps} = 5 years;
L_f = 10 years (project life); and
C_{es} = $300.
Summary: annual cost (bridge sensors) = $115/bridge.

2. Logic Circuitry (Eq. F-8)—

$$\text{Annual Cost} = (C_w + C_{el} + f_p\, C_p)[\mathrm{CRF}]_i^{L_f} + C_l[\mathrm{CRF}]_i^{L_l} + E_l$$

where:

$C_w = \$10$;
$C_{el} =$ included in C_{es} (see under preceding item 1);
$f_p = 1$ (entire cost charged to localized frost and ice, although system may also remind motorists under general snow or ice conditions; purpose of the system is strictly to deal with the localized problem, however);
$C_p = \$275$;
$C_l = \$750$;
$L_f = 10$ years (project life);
$L_l = 10$ years; and
$E_l = 4$ man-hours/month for 5 months at \$4/hr = \$80 plus power at \$2/month for 5 months = \$90 total.
Summary: annual cost (logic circuitry) = \$230/bridge.

3. Optional Display Warning Sign (Eq. F-10)—

$$\text{Annual Cost} = (f_p C_p + C_{ed})[\text{CRF}]_i^{L_f} + C_d[\text{CRF}]_i^{L_d} + E_d$$

where:

$f_p = 1$;
$C_p =$ included in C_p (see under preceding item 2);
$C_{ed} = \$100$/sign;
$C_d = \$800$: purchase cost (estimate based on conversations with highway engineers; dependent on sign complexity) = \$500 plus wire (bridge to sign) = \$100 plus installation = \$200;
$L_f = 10$ years (project life);
$L_d = 10$ years; and
$E_d =$ \$50/year, labor and parts.
Summary: annual cost (warning sign) = \$170/bridge.

On accumulating all costs (bridge sensors = \$115/bridge, logic circuitry = \$230/bridge, and warning signs = \$170/bridge), the annual costs for this system, installed for 10 years on each of 80 bridges, would be 80 (\$115 + \$230 + \$170) = \$41,200.

Benefits

In the following benefit examples five pavement conditions are considered, unless otherwise specified (the notation of Appendix B is used here): dry (m,n = 1); wet (m,n = 2); abrasives on ice (m,n = 3); localized ice, snow, or frost (m,n = 4); and generalized ice, snow, or frost (m,n = 5). The accident costs given in Table D-5 are used exclusively in all the numerical examples. The average cost of bridge accidents for each surface condition, except "abrasives on ice," was computed using a large regional mix of fatal, injury, and property-damage-only accidents. The average cost per accident for surface condition "abrasives on ice" is assumed to be the same as the average accident cost for generalized ice, snow, or frost.

The benefit equation applying to this example is Eq. B-4:

$$B_s = T_5 A_5 R_5 K_5 + T_4 A_4 R_4 K_4 + T_3 A_3 R_3 K_3$$

In this example it is assumed that the road surface conditions are unaltered by the detection and warning system. In addition, the general maintenance practice does not involve the use of abrasives, so that $T_3 = 0$. Also, the system is only activated by localized and generalized ice, snow, or frost conditions, and not by wet conditions. It is also assumed that the detector is 88 percent effective at detecting localized and generalized conditions (*3*) and that the effectiveness of the warning sign is about 25 percent. (Estimates of warning sign effectiveness are virtually nonexistent. However, from a recent field study of motorists' responses to warning signs (*3*), it was observed that about 50 percent of the motorists saw the sign when it was activated during hazardous conditions. Now, if one assumes that only about half of the 50 percent took corrective action so as to avoid a potential accident situation, then the effectiveness of the sign in reducing accidents would be about 25 percent.) Then, $A_5 = A_4 = 0.88(0.25) = 0.22$.

Substituting the foregoing assumptions, the exposure and accident rate data in Table C-13, and the accident cost data in Table D-5 into Eq. B-4 yields the annual benefit $B_s =$ 118(0.22) (0.135) (3,180) + 39(0.22) (0.310) (3,180) = \$19,600, or about \$245/bridge for the 80 bridges. The computed annual benefit assumes accident rates constant over the project life. This assumption may likely be a conservative (low) estimate considering the fact that the yearly number of accidents is growing at a finite rate. This same assumption is used in the other benefit examples presented in this appendix.

Benefit/Cost Ratio

The benefit/cost ratio (B_s/C) for this countermeasure system employed on all 80 bridges is $B_s/C =$ \$19,600/\$41,200 = 0.476.

Ohio Selected Bridges (Example B)

Costs

The same costs per bridge are assumed as in the preceding case. Thus, for 27 bridges and a 10-year time span, the annual costs would be 27(\$115 + \$230 + \$170) = \$13,900.

Benefits

The same assumptions employed in the previous benefit case regarding road surface exposure times and the effectiveness factors are used again in this case. Substituting into Eq. B-4 these assumptions, the previous A_n values, the exposure and accident rate data in Table C-14, and the accident cost data in Table D-5 yields the annual benefit $B_s =$ 236(0.22) (0.036) (3,180) + 78(0.22) (0.834) (3,180) = \$10,490, or about \$388/bridge for the 27 bridges.

Benefit/Cost Ratio

The benefit/cost ratio (B_s/C) for this countermeasure system is $B_s/C =$ \$10,490/\$13,900 = 0.754.

SECOND ILLUSTRATIVE EXAMPLE

The second example demonstrates the results of applying the bridge classification model to a group of bridges in the northeastern portion of Ohio. Two sets of bridges are considered—the same 27 bridges used in the first example, and the top nine of the 27 bridges arranged in a descending

order according to the predicted number of ice and snow accidents (top one-third of the sample).

In each instance, frost and ice detectors are installed on the bridges. These, in turn, activate motorist warning signs. No other specialized countermeasures will be included. A 10-year system life is also anticipated.

Twenty-Seven Ohio Bridges (Example C)

Costs

The same costs per bridge are assumed as in Example B. Thus, the annual costs would be 27(\$115 + \$230 + \$170) = \$13,900.

Benefits

The bridge classification model predicts a total of 16.95 ice and snow accidents for this set (see Table 4) compared to 15 accidents actually recorded (Table C-14). It is assumed that 43.2 percent and 56.8 percent of the predicted ice and snow accidents are caused by localized and generalized conditions, respectively. Combining this assumption with the exposure data in Table C-14 gives a predicted accident rate for localized ice, snow of 0.0939 accidents/hour; and for generalized ice, snow of 0.0408 accidents/hour.

The same assumptions used in the first example regarding road surface exposure times and effectiveness factors are again used in this case. Substituting into Eq. B-4 these assumptions, the previous A_n values, the exposure data in Table C-14, the previous accident rates, and the accident cost data in Table D-5 yields the annual benefit $B_s =$ 236(0.22)(0.0408)(3,180) + 78(0.22)(0.0939)(3,180) = \$11,860, or about \$439/bridge for the 27 bridges.

Benefit/Cost Ratio

The benefit/cost ratio B_s/C) for this countermeasure system is $B_s/C =$ \$11,860/\$13,900 = 0.853.

Nine Ohio Bridges (Example D)

Costs

The same costs per bridge are assumed as in Example B. Thus, the annual costs would be 9(\$115 + \$230 + \$170) = \$4,635.

Benefits

The bridge classification model predicts a total of 14 ice and snow accidents for the first nine bridges in Table 4. Dividing these 14 into localized and generalized ice and snow accidents according to the previous assumption—and combining with the exposure data in Table C-14—gives a predicted accident rate for localized ice or snow of 0.0775 accidents/hour and for generalized ice or snow of 0.0337 accidents/hour.

Using the assumptions of the previous example along with the preceding accident rates and the cost data in Table D-5 yields the annual benefit $B_s =$ 236(0.22)(0.0337)(3,180) + 78(0.22)(0.0775)(3,180) = \$9,795, or about \$1,088/bridge for the nine bridges.

Benefit/Cost Ratio

The benefit/cost ratio (B_s/C) for this countermeasure system is $B_s/C =$ \$9,795/\$4,635 = 2.113.

THIRD ILLUSTRATIVE EXAMPLE

The third example consists of evaluating two independent countermeasure proposals considered for a specific bridge(s). As a sample location, the bridge pair on I-95 at Route 1 near Spotsylvania, Va., is selected. This location has a high accident history and might well be of a type singled out for individual treatment.

One countermeasure proposal involves installing a frost and ice detection system on the twin bridges. The detectors will then activate motorist warning signs. The system used will be the same as that employed in the first example. The warning sign will be replaced at 10-year intervals during an assumed 30-year project life.

The second countermeasure proposal consists of a prediction/detection system coupled to a pavement heating system installed in each bridge deck. The Holley Highway Ice Condition Detection System will be used in the second proposal for illustrative purposes. A deck life of 30 years, unaffected by heating elements, is assumed, and it is also assumed that the heating element life is 30 years. Installation will be performed concurrently with initial construction or with deck replacement.

In both proposals, a single logic unit and dual pavement sensors will be utilized. The logic unit will be replaced at 10-year intervals, and the sensors at 5-year intervals. No other specialized countermeasures, such as maintenance alerting, will be included.

Warning Signs (Example E)

Costs

1. Bridge Sensors (Eq. F-7)—

Annual Cost $= C_{es}[\mathrm{CRF}]_i^{L_f} + C_{ps}[\mathrm{CRF}]_i^{L_{ps}} + E_{ps}$

where:

$E_{ps} =$ included with E_l (see under following item 2);
$C_{ps} =$ \$500 (two pairs of deck sensors) plus 30 man-hours at \$4/hr (see also C_l under following item 2) = \$620 total;
$L_{ps} =$ 5 years;
$L_f =$ 30 years (project life); and
$C_{es} =$ \$500.
Summary: annual cost (bridge sensors) = \$185.

2. Logic Circuitry (Eq. F-8)—

Annual Cost $= (C_w + C_{el} + f_p\, C_p)[\mathrm{CRF}]_i^{L_f} + C_l[\mathrm{CRF}]_i^{L_l} + E_l$

where:

$C_w =$ \$20;
$C_{el} =$ included in C_{es} under preceding item 1;
$f_p = 1$;
$C_p =$ \$275;
$C_l =$ \$750;

$L_f =$ 30 years;
$L_l =$ 10 years; and
$E_l =$ 6 man-hours/month for 5 months at \$4/hr = \$120 plus power at \$2/month for 5 months = \$130 total.
Summary: annual cost (logic circuitry) = \$255.

3. Optional Display Warning Sign (Eq. F-10)—

$$\text{Annual Cost} = (f_p C_p + C_{ed})[\text{CRF}]_i^{L_f} + C_d[\text{CRF}]_i^{L_d} + E_d$$

where:

$f_p = 1$;
$C_p =$ included in C_p under preceding item 2;
$C_{ed} =$ \$200 (two signs);
$C_d =$ purchase cost = \$1,000 plus wire (bridge to sign) = \$200 plus installation = \$400 = \$1,600;
$L_f =$ 30 years;
$L_d =$ 10 years; and
$E_d =$ \$100/year, labor and parts.
Summary: annual cost (warning signs) = \$330.

On accumulating all costs (bridge sensors = \$185, logic circuitry = \$255, and warning signs = \$330), the annual cost for this system would be \$185 + \$255 + \$330 = \$770.

Benefits

The benefit equation applying to this example is Eq. B-4:

$$B_s = T_5 A_5 R_5 K_5 + T_4 A_4 R_4 K_4 + T_3 A_3 R_3 K_3$$

The same assumptions employed in the first example regarding road surface exposure times and the effectiveness factors are used again in this case. Substituting into Eq. B-4 these assumptions, the associated A_n values, the exposure and accident rate data in Table C-16, and the accident cost data in Table D-5 yields the annual benefit $B_s = 56.1(0.22)(0.0250)(3{,}180) + 18.7(0.22)(0.0588)(3{,}180) =$ \$1,750.

Benefit/Cost Ratio

The benefit/cost ratio (B_s/C) for this countermeasure system is $B_s/C =$ \$1,750/\$770 = 2.273.

Pavement Heating (Example F)

Costs

1. Bridge Sensors (Eq. F-7)—

$$\text{Annual Cost} = C_{es}[\text{CRF}]_i^{L_f} + C_{ps}[\text{CRF}]_i^{L_{ps}} + E_{ps}$$

where:

$E_{ps} =$ included with E_l (see under following item 2);
$C_{ps} =$ \$1,200 including air sensor and two pairs of deck sensors plus 40 man-hours at \$4/hr = \$1,360;
$L_{ps} =$ 5 years;
$L_f =$ 30 years; and
$C_{es} =$ \$500.
Summary: annual cost (bridge sensors) = \$360.

2. Logic Circuitry (Eq. F-8)—

$$\text{Annual Cost} = (C_w + C_{el} + f_p C_p)[\text{CRF}]_i^{L_f} + C_l[\text{CRF}]_i^{L_l} + E_l$$

where:

$C_w =$ \$20;
$C_{el} =$ included in C_{es} under preceding item 1;
$f_p = 1$;
$C_p =$ included in C_p under following item 3;
$C_l =$ \$1,550 plus 10 man-hours at \$4/hr = \$1,590 total;
$L_f =$ 30 years;
$L_l =$ 10 years; and
$E_l =$ 8 man-hours/month for 5 months at \$4/hr = \$160 plus power at \$2/month for 5 months = \$170 total.
Summary: annual cost (logic circuitry) = \$390.

3. Heating System (Eq. F-11)—

$$\text{Annual Cost} = f_n\left[\left(C_{ho} + \frac{[Y_p + L_p - L_{pn}]C_{pn}}{L_{pn}} + C_p + C_{eh}\right)[\text{CRF}]_i^{L_f} + \left(C_h + \frac{[L_{pn} - L_p]C_{pn}}{L_{pn}}\right)[\text{CRF}]_i^{L_p} + E_h\right]$$

where:

$f_n = 1$;
$C_{ho} =$ included in C_h;
$Y_p = 0$;
$L_p = L_{pn} =$ 30 years;
$C_{pn} =$ not needed because of life assumptions used;
$C_p =$ \$275;
$C_{eh} =$ \$2,500;
$L_f =$ 30 years;
$C_h =$ \$4/sq ft, 2 spans, 150 × 24 ft = \$28,800; and
$E_h =$ \$0.30/sq ft × 7,200 sq ft = \$2,160 for power plus 4 man-hours/month for 5 months at \$4 = \$2,240 total.
Summary: annual cost (heating system) = \$4,535.

On accumulating all costs (bridge sensors = \$360, logic circuitry = \$390, and heating system = \$4,535), the annual cost for the entire system over 30 years is thus \$360 + \$390 + \$4,535 = \$5,285.

Benefits

The benefit equation applying to this example is Eq. B-3:

$$\begin{aligned} B_H = {} & T_5(R_5 K_5 - P_{55} R_5 K_5 - P_{52} R_2 K_2 - P_{51} R_1 K_1) \\ & + T_4(R_4 K_4 - P_{44} R_4 K_4 - P_{42} R_2 K_2 - P_{41} R_1 K_1) \\ & + T_3(R_3 K_3 - P_{33} R_3 K_3 - P_{32} R_2 K_2 - P_{31} R_1 K_1) \\ & + T_2(R_2 K_2 - P_{22} R_2 K_2 - P_{21} R_1 K_1) \end{aligned}$$

In this example the road surface conditions are altered by the pavement heating system. In addition, the general maintenance practice does not involve the use of abrasives, so that $T_3 = 0$. The detection/prediction-heating system is assumed to be effective only for localized and generalized ice, snow, or frost conditions. It is also assumed that the detector is 80 percent effective at detecting and predicting localized and generalized conditions. (This detection/prediction system is less effective than the one used in the first example because of the increased probability of the device to produce more false alarms (or lack of alarms) than a pure detection device in its attempt to predict the occurrence of frost.) Furthermore, it is assumed that the pavement heat-

ing system is capable of removing 95 percent of the ice, snow, or frost conditions, 80 percent of the time. In other words, the system is about 75 percent (95 percent times 80 percent in round numbers) effective in preventing both localized and generalized icing conditions. In addition, 0.2 and 0.8 of the localized icing time prevented are converted to wet and dry pavement conditions, respectively. The generalized icing time prevented is divided equally into wet and dry conditions.

Writing these assumptions in terms of the notation of Eq. B-3 yields:

$P_{55} = P_{44} = 0.25$;
$P_{52} = P_{51} = (0.5)(0.75) = 0.375$;
$P_{42} = (0.2)(0.75) = 0.15$;
$P_{41} = (0.8)(0.75) = 0.60$;
$P_{22} = 1.0$;
$P_{21} = 0$; and
P_{33}, P_{32}, and P_{31} = not needed because $T_3 = 0$.

Substituting into Eq. B-3 the foregoing relationships, the exposure and accident rates in Table C-16, and the accident cost data in Table D-5 yields the annual benefit $B_H = 56.1$ [0.025 (3,180) − 0.25(0.0250)(3,180) − 0.375(0.000960)(4,210) − 0.375(0.000196)(6,840)] + 18.7(0.0588)(3,180) − 0.25(0.0588)(3,180) − 0.15(0.000960)(4,210) − 0.60(0.000196)(6,840) + 1,042(0.000960)(4,210) − 1.0(0.000960)(4,210) = \$5,825.

Benefit/Cost Ratio

The benefit/cost ratio (B_H/C) for the entire pavement heating countermeasure system is B_H/C = \$5,825/\$5,285 = 1.102.

FOURTH ILLUSTRATIVE EXAMPLE

The fourth example consists of an area-wide system. Detection is accomplished through utilization of existing state police patrols who are asked to report localized icy bridges to the highway maintenance area. Each area is manned by a watchman, who also has other duties. Upon alert, he summons crews who then patrol their assigned road sections and spread deicing chemicals as required.

Three geographic regions are selected as representing moderate, heavy, and light amounts of hazardous winter weather conditions. These regions are south-central Iowa, northeast Ohio, and the Texas Panhandle, respectively.

Bridge deterioration is one of the important cost elements to be considered. The bridge structure is assumed to be designed for a 50-year life. Ignoring the effects of deicing chemicals, it is also assumed that a 2-in. AC overlay placed down every 15 years is the only maintenance that would be required. (The widely publicized degrading effects of studded tires are ignored, here and elsewhere, as their long-term use has not yet been widespread and their usage in the future is still an imponderable.)

The use of deicing chemicals, as discussed in Appendix F, leads to spalling and scaling, both of which tend to shorten the useful bridge life. To counteract these effects, any of several special maintenance practices may be employed (*9*). For purposes of illustration, it is assumed that an initial epoxy sealer is applied to the deck to minimize spalling, and a 1-in. AC overlay is applied to protect the epoxy and to minimize scaling. After a period, L_{od}, a second overlay is required. Then, following a second period of L_{od}, the overlay must be stripped off, a new epoxy seal applied, and the process repeated.

The police patrol gives rise to benefits for two reasons. First, they may spot hazardous conditions (and initiate the treatment chain-of-events) that would otherwise go untreated. Second, their warning may simply initiate more rapid treatment than would occur otherwise, thus shortening the duration of the hazard but not adding to the treatment costs.

South-Central Iowa (Example G)

The region selected includes Des Moines, a large portion of I-80, and the southern portion of I-35. A 20-county region encompassing 40 maintenance areas, 909 bridges, and 2,250 patrol-miles is used. A patrol-mile is generally 2 lane-miles; 1 mile of typical rural Interstate highway would account for 2 patrol-miles or 4 lane-miles.

Costs

1. Communication System (Eq. F-1)—Use existing system.

2. Facility Watch (Eq. F-3)—

Annual Cost $= F_w K_w N_w$

where, for each maintenance area:

$f_w = 0.10$;
K_w = 1 man watch, 8-hr shift at \$4/hr = \$32; and
N_w = each night for 5 months/year = \$150.

Summary: annual cost (facility watch) = \$480/maintenance area.

3. Dispense Chemicals (Eq. F-14)—

$$\text{Annual Cost} = N_d\left[K_{mr} + D_d\left(K_v + \frac{K_d}{V_d}\right)\right]$$

where, for each maintenance area:

N_d = 10 alerts/year (a total of 65 applications of deicing chemicals assumed used in each area for the combined generalized and localized control; the ratio of the number of applications for localized control to the number of total applications assumed equal to that ratio recorded for the Ames, Iowa, bridge (see Table C-10); thus, $N_d = (9/49)65 \approx 10$);
K_{mr} = 2 man-hours at \$4/hr = \$8;
D_d = 25 miles/vehicle trip and 3 trips/alert = 75 miles;
K_v = \$0.10;
K_d = \$4; and
V_d = 35 mph.

Summary: annual cost (dispense chemicals) considering three vehicles used per maintenance area = \$720/ maintenance area.

4. Purchase, Prepare, and Store Chemicals (Eq. F-13)—

Annual Cost $= 1.05\, f_m\, W_m(K_{sc}\, P_{sc} + K_{cc}\, P_{cc} + K_{ac}\, P_{ac})$

where, for the entire region:

f_m = total chemical tonnage for the region: 55 applications for generalized control at 250 lb/lane-mile, 2 lanes/patrol-mile, 2,250 patrol-miles = 30,938 tons; added tonnage on bridges for localized icing: 10 applications at 250 lb/lane-mile, 2 lanes/patrol-mile, 909 bridges, 150 ft/bridge = 64.6 tons; thus $f_m = 64.6/31{,}003 = 0.0021$;
W_m = 31,003 tons;
K_{sc} = \$15/ton;
P_{sc} = assuming a ratio of 3:1 salt to CaCl = 0.75;
K_{cc} = \$50/ton;
P_{cc} = 0.25; and
K_{ac}, P_{ac} = not used.

Summary: annual cost (purchase, prepare, and store chemicals) = \$1,610 for the entire region.

5. Repair and Maintenance of Bridge Decks due to Deicing Chemicals (Eq. F-15)—

Annual Cost =

$$f_p A \left\{ [\mathrm{CRF}]_i^{L_f} \left[\sum_{a=1}^{q} (U_o [\mathrm{PWF}]_i^{aL_{od}} + U_s [\mathrm{PWF}]_i^{2aL_{od}}) - \sum_{b=1}^{r} (U_o [\mathrm{PWF}]_i^{bL_{oo}} + U_s [\mathrm{PWF}]_i^{2bL_{oo}}) + U_l \left(\sum_{c=1}^{s} [\mathrm{PWF}]_i^{cL_{ld}} - \sum_{d=1}^{t} [\mathrm{PWF}]_i^{dL_{lo}} \right) \right] + U_p \left[\frac{A_{sd} - A_{so}}{A} \right] \right\}$$

where, for each bridge:

$f_p = 10/65$;
A = 30 ft by 150 ft = 4,500 sq ft; and
L_f = 50 years.

Assuming that no deicing chemicals (or tire studs) are used and that the deck must be resurfaced with a 2-in. AC cover at 15-year intervals gives $L_{oo} = 15$ years. Assuming also that, when deicing chemicals are used, in 1-in. AC overlay is applied every 10 years. Thus:

L_{od} = 10 years;
L_{ld}, L_{lo} = not needed because a linseed oil seal is not considered;
U_o = \$0.10/sq ft;
U_s = \$0.60/sq ft;
U_l = not needed;
U_p = \$4.25/sq ft;
A_{sd} = 8 sq ft; and
A_{so} = 4 sq ft.

Summary: annual cost (bridge deterioration due to localized deicing countermeasure) = \$10.90/bridge.

On recapitulating and accumulating all costs (communication system = 0, facility watch = \$480/maintenance area, dispense chemicals = \$720/maintenance area, chemicals = \$1,610 total, and bridge maintenance = \$10.90/bridge), the annual costs for this system for the entire region are \$480 × 40 areas + \$720 × 40 areas + \$1,610 + \$10.90 × 909 bridges = \$19,200 + \$28,800 + \$1,610 + \$9,910 = \$59,520.

Benefits

The benefit equation applying to this example is Eq. B-5:

$$\begin{aligned} B_D = {} & T_5(R_5 K_5 - P_{55} R_5 K_5 - P_{52} R_2 K_2 - P_{51} R_1 K_1) \\ & + T_4(R_4 K_4 - P_{44} R_4 K_4 - P_{42} R_2 K_2 - P_{41} R_1 K_1) \\ & + T_3(R_3 K_3 - P_{33} R_3 K_3 - P_{32} R_2 K_2 - P_{31} R_1 K_1) \\ & + T_1(R_1 K_1 - P_{14} R_4 K_4 - P_{12} R_2 K_2 - P_{11} R_1 K_1) \end{aligned}$$

In this example, there are two time delays associated with the detection and subsequent treatment of the localized icing conditions. One is due to the state highway police in detecting the hazardous condition; the other is due to the time required by the local maintenance crews to arrive at the bridges and also the time after treatment until the hazardous condition is arrested. With the assumptions that the state highway police are 75 percent effective in detection and that maintenance is 67 percent effective in treatment, the two in combination mean that the system is (0.75)(0.67) = 0.5, or 50 percent effective in preventing localized icing conditions from occurring. The localized icing time prevented is divided equally into wet and dry conditions. In addition, it is assumed that the generalized icing condition is unaltered by this detection and countermeasure system, because maintenance will normally be self-alerting to major storm conditions. It is also assumed that abrasives are not used in the general maintenance practice, so that $T_3 = 0$.

Now, writing the foregoing assumptions in terms of the notation of Eq. B-5 yields:

$P_{55} = 1.0$;
$P_{52} = P_{51} = 0$;
$P_{44} = 0.5$;
$P_{42} = P_{41} = 0.25$;
$P_{11} = 1.0$;
$P_{14} = P_{12} = 0$; and
P_{33}, P_{32}, and P_{31} = not needed because $T_3 = 0$.

Substituting into Eq. B-5 these relationships, the exposure and accident rates in Table C-12, and the accident cost data in Table D-5 yields the annual benefit $B_D = 118[0.260(3{,}180) - 1.0(0.260)(3{,}180)] + 39[0.597(3{,}180) - 0.5(0.597)(3{,}180) - 0.25(0.0397)(4{,}210) - 0.25(0.0133)(6{,}840)] + 7{,}546[0.0133(6{,}840) - 1.0(0.0133)(6{,}840)] =$ \$34,505, or about \$38/bridge for the 909 bridges.

Benefit/Cost Ratio

The benefit/cost ratio (B_D/C) for an area-wide localized deicer countermeasure system in the south-central Iowa region is B_D/C = \$34,505/\$59,520 = 0.580.

Northeastern Ohio (Example H)

A region containing 1,100 patrol-miles and 550 bridges was selected in the heavy snow portion of Ohio. Twelve maintenance areas are assumed, with five routes per area.

Costs

1. Communication System (Eq. F-1)—Same as Iowa: use existing system.

2. Facility Watch (Eq. F-3)—Same as Iowa: \$480/maintenance area.

3. Dispense Chemicals (Eq. F-14)—Same as Iowa except that five vehicles are used per maintenance area to cover the area. Also, a total of 130 applications of deicing chemicals are assumed used in each area for the combined localized and generalized control. The ratio of the number of applications for localized control to the number of total applications is assumed equal to the ratio recorded for Ravenna, Ohio, bridges (see Table C-10). Thus, $N_d = (9/123)\ 130 \approx 10$ alerts/year.

Summary: annual cost (dispense chemicals) = \$1,200/maintenance area.

4. Purchase, Prepare, and Store Chemicals (Eq. F-13)—

Annual Cost $= 1.05\, f_m\, W_m(K_{sc}\, P_{sc} + K_{cc}\, P_{cc} + K_{ac}\, P_{ac})$

where, for the entire region:

f_m = total chemical tonnage for the region: 120 applications for generalized control at 250 lb/lane-mile, 2 lanes/patrol-mile, 1,100 patrol-miles = 33,000 tons; added tonnage on bridges for localized icing: 10 applications at 250 lb/lane-mile, 2 lanes/patrol-mile, 550 bridges, 150 ft/bridge = 39 tons; thus, $f_m = 39/33{,}039 = 0.0012$;

W_m = 33,039 tons;

K_{sc} = \$10/ton;

P_{sc} = assuming a ratio of 3:1 salt to CaCl = 0.75;

K_{cc} = \$40/ton;

P_{cc} = 0.25; and

K_{ac}, P_{ac} = not used.

Summary: annual cost (purchase, prepare, and store chemicals) = \$715 for the entire region.

5. Repair and Maintenance of Bridge Decks due to Deicing Chemicals (Eq. F-15)—Same as Iowa except $f_p = 10/130$ and because more deicers are used in this region, it is assumed that the AC overlay and epoxy seal will be applied more often, say every 9 and 18 years, respectively. Thus, $L_{od} = 9$ years.

Summary: annual cost (bridge deterioration due to localized deicing countermeasure) for the 30 ft by 150 ft bridge = \$6.74/bridge.

On accumulating all costs (communication system = 0, facility watch = \$480/maintenance area, dispense chemicals = \$1,200/maintenance area, chemicals = \$715, and bridge maintenance = \$6.74/bridge), the annual costs for the entire region are \$480 × 12 areas + \$1,200 × 12 areas + \$715 + \$6.74 × 550 bridges = \$5,760 + \$14,400 + \$715 + \$3,710 = \$24,585.

Benefits

The benefit equation applying to this example is Eq. B-5. The same assumptions employed in the previous case are used here also. Substituting into Eq. B-5 the previous expressions, the exposure and accident rates in Table C-14, and the accident cost data in Table D-5 yields the annual benefit $B_D = 236[0.036(3{,}180) - 1.0(0.036)(3{,}180)] + 78[0.0834(3{,}180) - 0.5(0.0834)(3{,}180) - 0.25(0.00517)(4{,}210) - 0.25(0.00198)(6{,}840)] + 7{,}091[0.00198(6{,}840) - 1.0(0.00198)(6{,}840)]$ = \$9,655, or about \$18/bridge for the 550 bridges.

Benefit/Cost Ratio

The benefit/cost ratio (B_D/C) for an area-wide localized deicing countermeasure system in the northeastern Ohio region is B_D/C = \$9,655/\$24,585 = 0.393.

Texas Panhandle (Example I)

The Panhandle region, including Amarillo, is chosen for analysis. This is a 17-county region, containing approximately 2,900 patrol-miles and 1,000 bridges. It is assumed that there are approximately two maintenance areas per county, four patrol routes per area, and 30 patrol-miles per route.

Costs

1. Communication System (Eq. F-1)—Same as Iowa: use existing system.

2. Facility Watch (Eq. F-3)—Same as Iowa: \$480/maintenance area.

3. Dispense Chemicals (Eq. F-14)—Same as Iowa except:

D_d = 30 miles/trip, 3 trips/alert = 90 miles;

N_d = 15 alerts/year (a total of 35 applications of deicing chemicals assumed used in each area for the combined localized and generalized control; the ratio of the number of applications for localized control to the number of total applications assumed equal to the ratio recorded for the Amarillo bridge (see Table C-10); thus, $N_d = (11/24)35 \approx 15$).

Summary: annual cost (dispense chemicals) = \$1,635/maintenance area.

4. Purchase, Prepare, and Store Chemicals (Eq. F-13)—

Annual Cost $= 1.05\, f_m\, W_m(K_{sc}\, P_{sc} + K_{cc}\, P_{cc} + K_{ac}\, P_{ac})$

where, for the entire region:

f_m = total chemical tonnage for the region: 20 applications for generalized control at 250 lb/lane-mile, 2 lanes/patrol-mile, 2,900 patrol-miles = 14,500 tons; added tonnage on bridges for localized icing: 15 applications at 250 lb/lane-mile, 2 lanes/patrol-mile, 1,000 bridges, 150 ft/bridge = 106.5 tons; thus, $f_m = 106.5/14{,}607 = 0.0073$;

W_m = 14,607 tons;

K_{sc} = \$18.36/ton; and

P_{sc} = assuming salt only = 1.0.

Summary: annual cost (purchase, prepare, and store chemicals) = \$2,055 for the entire region.

5. Repair and Maintenance of Bridge Decks due to Deicing Chemicals (Eq. F-15)—Same as Iowa except $f_p = 15/35$ and a longer lifetime of the seal and overlay is assumed because of the smaller usage of deicers; for example, $L_{od} = 13$ years.

Summary: annual cost (bridge deterioration due to localized deicing countermeasure) for the 30-ft by 150-ft bridge = \$12.20/bridge.

On accumulating all costs (communication system = 0, facility watch = \$480/maintenance area, dispense chemicals = \$1,635/maintenance area, chemicals = \$2,055, and bridge maintenance = \$12.20/bridge), the annual costs for the entire region are \$480 × 34 areas + \$1,635 × 34 areas + \$2,055 + \$12.20 × 1,000 bridges = \$16,320 + \$55,590 + \$2,055 + \$12,200 = \$86,165.

Benefits

The benefit equation applying to this example is Eq. B-5. The same assumptions employed in the previous case are again used here. Substituting into Eq. B-5 the previous expressions, the exposure and accident rates in Table C-13, and the accident cost data in Table D-4 yields the annual benefit $B_D = 54[0.243(3{,}180) - 1.0(0.243)(3{,}180)] + 18[0.550(3{,}180) - 0.5(0.550)(3{,}180) - 0.25(0.0105)(4{,}210) - 0.25(0.00179)(6{,}840)] + 7{,}828[0.00179(6{,}840) - 1.0(0.00179)(6{,}840)] = \$15{,}490$, or about \$15/bridge for the 1,000 bridges.

Benefit/Cost Ratio

The benefit/cost ratio (B_D/C) for an area-wide localized deicing countermeasure system in the Texas Panhandle region is $B_D/C = \$15{,}490/\$86{,}165 = 0.180$.

FIFTH ILLUSTRATIVE EXAMPLE

The fifth example is similar to the fourth except that frost and ice detectors are used instead of relying on the police patrols. Therefore, quick response to hazardous conditions is assumed. The watchman in the fourth example is replaced by a receiver in the home of the resident maintenance engineer or his foreman. A MARS alert system is utilized. Each maintenance area instruments two bridges as indicators for the area, and all areas are assumed to be in communication via an existing network. Again, three geographic areas are used as illustrations.

South-Central Iowa (Example J)

From the fourth example, the facility watch costs are deleted and sensors, logic circuitry, and communication equipment are added.

Costs

1. Bridge Sensors (Eq. F-7)—Same as the first example except $L_f = 50$ years. Thus, annual cost (bridge sensors) = \$95/bridge.
2. Logic Circuitry (Eq. 7-8)—Same as the first example except $L_f = 50$ years. Thus, annual cost (logic circuitry) = \$210/bridge.
3. Communication System (Eq. F-1)—

$$\text{Annual Cost} = f_c\{C_c[\text{CRF}]_i^{L_c} + E_c\}$$

where:

$f_c = 1.0$;
C_c = \$1,563 for transmitter, antenna, power pack wiring plus installation at \$16 for 4 hr at \$4/man-hour = \$1,579/bridge; or \$3,158/maintenance area (2 bridges) plus \$144 for receiver = \$3,302/maintenance area;
$L_c = 13$ years; and
E_c = 8 hr/year at \$4/man-hour = \$32.
Summary: annual cost (communication system) = \$405/maintenance area.

On accumulating all costs (communication system = \$405/area, bridge sensors = \$95/bridge, logic circuitry = \$210/bridge, dispense chemicals = \$720/area, chemicals = \$1,610 total, and bridge maintenance = \$10.90/bridge), the annual costs for this system for the entire region are \$405 × 40 areas + \$95 × 80 bridges + \$210 × 80 bridges + \$720 × 40 areas + \$1,610 + \$10.90 × 909 bridges = \$16,200 + \$7,600 + \$16,800 + \$28,800 + \$1,610 + \$9,910 = \$80,920.

Benefits

The benefit equation applying to this example is again Eq. B-5.

In this example, the road conditions are altered according to the following assumptions. The detector is 88 percent effective at detecting localized and generalized ice, snow, or frost conditions. Maintenance treatment is again considered 67 percent effective. Therefore, the system is about 60 percent effective in preventing, or removing, localized icing conditions. In addition, the system is assumed to be about 20 percent effective in preventing generalized bridge icing conditions due to the increased alertness of maintenance as a result of the warning signal generated by the detection devices. Both the localized and generalized icing times prevented by the system are divided equally into wet and dry pavement conditions. Also, it is assumed that abrasives are not used in the general maintenance practice, so that $T_3 = 0$.

Writing the foregoing assumptions in terms of the notation of Eq. B-5 yields:

$P_{55} = 0.8$;
$P_{52} = P_{51} = 0.1$;
$P_{44} = 0.4$;
$P_{42} = P_{41} = 0.3$;
$P_{14} = P_{12} = 0$;
$P_{11} = 1.0$; and
P_{33}, P_{32}, and P_{31} = not needed because $T_3 = 0$.

Substituting into Eq. B-5 the foregoing relationships, the exposure and accident rates in Table C-12, and the accident cost data in Table D-5 yields the annual benefit $B_D = 118[0.260(3{,}180) - 0.8(0.260)(3{,}180) - 0.1(0.0397)(4{,}210) - 0.1(0.0133)(6{,}840)] + 39[0.597(3{,}180) - 0.4(0.597)(3{,}180) - 0.3(0.0397)(4{,}210) - 0.3(0.0133)(6{,}840)] + 7{,}546[0.0133(6{,}840) - 1.0(0.0133)(6{,}840)] = \$57{,}870$, or about \$64/bridge for the 909 bridges.

Benefit/Cost Ratio

The benefit/cost ratio (B_D/C) for the areawide system in the south-central Iowa region is $B_D/C = \$57{,}870/\$80{,}920 = 0.715$.

Northeastern Ohio (Example K)

Costs

From Example H and Example J:

Communication system	= \$405/area;
Bridge sensors	= \$95/bridge;
Logic circuitry	= \$210/bridge;
Dispense chemicals	= \$1,200/area;
Chemicals	= \$715 total; and
Bridge maintenance	= \$6.75/bridge.

On accumulating the foregoing costs, the annual costs for the entire region are \$405 × 12 areas + \$95 × 24 bridges + \$210 × 24 bridges + \$1,200 × 12 areas + \$715 + \$6.74 × 550 bridges = \$4,860 + \$2,280 + \$5,040 + \$14,400 + \$715 + \$3,710 = \$31,005.

Benefits

The same assumptions made in the previous case are employed here also. Substituting into Eq. B-5 the previous expressions, the exposure and accident rates in Table C-14, and the accident cost data in Table D-5 yields the annual benefit $B_D = 236[0.0360(3{,}180) - 0.8(0.0360)(3{,}180) - 0.1(0.00517)(4{,}210) - 0.1(0.00198)(6{,}840)] + 78[0.0834(3{,}180) - 0.4(0.0834)(3{,}180) - 0.3(0.00517)(4{,}210) - 0.3(0.00198)(6{,}840)] + 7{,}091[0.00198(6{,}840) - 1.0(0.00198)(6{,}840)] = \$16{,}155$, or about \$29/bridge for the 550 bridges.

Benefit/Cost Ratio

The benefit/cost ratio (B_D/C) for the areawide system in the northeastern Ohio region is $B_D/C = \$16{,}155/\$31{,}005 = 0.521$.

Texas Panhandle (Example L)

Costs

From Example I and Example J:

Communication system	= \$405/area;
Bridge sensors	= \$95/bridge;
Logic circuitry	= \$210/bridge;
Dispense chemicals	= \$1,635/area;
Chemicals	= \$2,055 total; and
Bridge maintenance	= \$12.20/bridge.

On accumulating all of the foregoing costs, the annual costs for the entire region are \$405 × 34 areas + \$95 × 68 bridges + \$210 × 68 bridges + \$1,635 × 34 areas + \$2,055 + \$12.20 × 1,000 bridges = \$13,770 + \$6,460 + \$14,280 + \$55,590 + \$2,055 + \$12,200 = \$104,355.

Benefits

The same assumptions used in the previous case are again used here. Substituting into Eq. B-5 the previous expressions, the exposure and accident rates in Table C-15, and the accident cost data in Table D-5 yields the annual benefit $B_D = 54[0.243(3{,}180) - 0.8(0.243)(3{,}180) - 0.1(0.0105)(4{,}210) - 0.1(0.00179)(6{,}840)] + 18[0.550(3{,}180) - 0.4(0.550)(3{,}180) - 0.3(0.0105)(4{,}210) - 0.3(0.00179)(6{,}840)] + 7{,}828[0.00179(6{,}840) - 1.0(0.00179)(6{,}840)] = \$26{,}625$, or about \$27/bridge for the 1,000 bridges.

Benefit/Cost Ratio

The benefit/cost ratio (B_D/C) for the areawide system in the Texas Panhandle region is $B_D/C = \$26{,}625/\$104{,}355 = 0.255$.

SIXTH ILLUSTRATIVE EXAMPLE

The sixth example is similar to the fifth, except on alert of localized icing conditions, the maintenance crews are dispatched to spread noncorrosive deicing chemicals on all the bridges. The noncorrosive chemical used is tetrapotassium pyrophosphate (TKPP). Field tests of this chemical are discussed in a report dealing with the evaluation of deicing chemicals (*45*). These tests indicated that a 30 percent solution (by weight) of TKPP applied at a rate of 0.01 lb/sq ft of bridge deck surface was an effective frost preventive in mild climates (where temperatures rarely go below 25 F).

In this example it is assumed that a 30 percent solution of TKPP is sprayed on the bridge decks at the rate of 0.01 lb/sq ft. The chemical is used to combat localized icing conditions once detected, rather than as a preventive. It is also assumed that the life of an asphalt overlay and the average annual area of spall damage are unaffected by the use of TKPP. Thus, bridge deck deterioration is not considered as one of the cost elements. The cost of TKPP is assumed to be 15 times that of salt. Three geographic areas are again used as illustrations.

South-Central Iowa (Example M)

From the fifth example, the cost to purchase, prepare, and store the chemicals is modified and the bridge maintenance costs are deleted.

Costs

1. Purchase, Prepare, and Store Chemicals (Eq. F-13)—

Annual Cost $= 1.05\, f_m\, W_m(K_{sc}\, P_{sc} + K_{cc}\, P_{cc} + K_{ac}\, P_{ac})$

where, for the entire region:

$f_m\, W_m$ = total chemical tonnage for localized icing: 10 applications at 0.01 lb/sq ft, 30 percent solution TKPP, 30-ft by 150-ft bridges, 909 bridges = 61.4 tons;

K_{sc} = TKPP used in place of salt and assumed to cost 15 times that of salt; thus K_{sc} = \$15/ton times 15 = \$225/ton;

P_{sc} = 1.0; and

$K_{cc}, P_{cc}, K_{ac}, P_{ac}$ = not used.

Summary: annual cost (purchase, prepare, and store chemicals) = \$14,505 for the entire region.

Now, from the foregoing and Example J:

Communication system	= \$405/area;
Bridge sensors	= \$95/bridge;
Logic circuitry	= \$210/bridge;
Dispense Chemicals	= \$720/area;
Chemicals	= \$14,505 total; and
Bridge maintenance	= 0.

On accumulating all of these costs, the annual costs for this system for the entire region are \$405 × 40 areas + (\$95 + \$210) × 80 bridges + \$720 × 40 areas + \$14,505 = \$16,200 + \$24,400 + \$28,800 + \$14,505 = \$83,905.

Benefits

The benefit equation applying to this example is Eq. B-5. The same assumptions used in Example J are again used here. Thus, the annual benefit for this system is $B_D =$ \$57,870.

Benefit/Cost Ratio

The benefit/cost ratio (B_D/C) for an areawide system employing noncorrosive deicing chemicals in the south-central Iowa region is $B_D/C =$ \$57,870/\$83,905 = 0.690.

Northeastern Ohio (Example N)

Costs

1. Purchase, Prepare, and Store Chemicals (Eq. F-13)—

$$\text{Annual Cost} = 1.05\, f_m\, W_m(K_{sc}\, P_{sc} + K_{cc}\, \widehat{P}_{cc} + K_{ac}\, P_{ac})$$

where, for the entire region:

$f_m\, W_m$ = total tonnage for localized icing: 10 applications at 0.01 lb/sq ft, 30 percent solution TKPP, 30-ft by 150-ft bridges, 550 bridges = 37.1 tons;
K_{sc} = \$10/ton for salt times 15 = \$150/ton; and
P_{sc} = assuming TKPP only = 1.0.
Summary: annual cost (purchase, prepare, and store chemicals) = \$5,845 for the entire region.

2. Communication System, Bridge Sensors, Logic Circuitry, Dispense Chemicals—From the foregoing and Example K:

Communication system	= \$405/area;
Bridge sensors	= \$95/bridge;
Logic circuitry	= \$210/bridge;
Dispense chemicals	= \$1,200/area;
Chemicals	= \$5,845 total; and
Bridge maintenance	= 0.

On accumulating these costs, the annual costs for the entire region are \$405 × 12 areas + (\$95 + \$210) × 24 bridges + \$1,200 × 12 areas + \$5,845 = \$4,860 + \$7,320 + \$14,400 + \$5,845 = \$32,425.

Benefits

The annual benefit is computed from Eq. B-5 using the same assumptions made in the previous case. Thus, from Example K $B_D =$ \$16,155.

Benefit/Cost Ratio

The benefit/cost ratio (B_D/C) for an areawide system employing noncorrosive chemicals in the northeastern Ohio region is $B_D/C =$ \$16,155/\$32,425 = 0.498.

Texas Panhandle (Example O)

Costs

1. Purchase, Prepare, and Store Chemicals (Eq. F-13)—

$$\text{Annual Cost} = 1.05\, f_m\, W_m(K_{sc}\, P_{sc} + K_{cc}\, P_{cc} + K_{ac}\, P_{ac})$$

where, for the entire region:

$f_m\, W_m$ = total tonnage for localized icing: 15 applications at 0.01 lb/sq ft, 30 percent solution TKPP, 30-ft by 150-ft bridges, 1,000 bridges = 101.3 tons;
K_{sc} = \$18.36/ton for salt times 15 = \$275.40/ton; and
P_{sc} = assuming TKPP only = 1.0.
Summary: annual cost (purchase, prepare, and store chemicals) = \$29,295 for the entire region.

2. Communication System, Bridge Sensors, Logic Circuitry, Dispense Chemicals—From the foregoing and Example L:

Communication system	= \$405/area;
Bridge sensors	= \$95/bridge;
Logic circuitry	= \$210/bridge;
Dispense chemicals	= \$1,635/area;
Chemicals	= \$29,295 total; and
Bridge maintenance	= 0.

On accumulating these costs, the annual costs for the entire region are \$405 × 34 areas + (\$95 + \$210) × 68 bridges + \$1,635 × 34 areas + \$29,295 = \$13,770 + \$20,740 + \$\$55,590 + \$29,295 = \$119,395.

Benefits

The annual benefit is again computed from Eq. B-5 using the same assumptions made in the previous case. Thus, from Example L $B_D =$ \$26,625.

Benefit/Cost Ratio

The benefit/cost ratio (B_D/C) for an areawide system employing noncorrosive chemicals in the Texas Panhandle region is $B_D/C =$ \$26,625/\$119,395 = 0.223.

APPENDIX I

DEVELOPMENT OF A BRIDGE CLASSIFICATION MODEL

The objective of this development is to demonstrate the construction of a mathematical model for predicting the number of ice and snow accidents per year on a bridge, given various characteristics of that bridge. With this kind of model, the highway department administrator can rank bridges by degree of hazard as a basis for selecting candidate bridges for the application of countermeasures.

A direct (and common) procedure in similar situations is to predict the response of interest using multiple regression (*5*). (That is, multiple regression might be employed with the response, Y, defined as the number of (ice and snow) accidents per bridge per year.) However, a multiple regression approach here is not desirable for several reasons. A fundamental assumption of any regression analysis is that the conditional distribution of Y, given the independent variable set, $X_1, \ldots, X_n$, is normal. Available bridge accident data and, in particular, the accidents under snowy and icy pavement conditions show that this assumption is violated.

This lack of normality is readily demonstrated by a simple calculation. Assume that bridges are involved in only their share of accidents on a mileage basis. Using, for illustrative purposes, a total accident rate of three accidents per million vehicle-miles (typical of Interstate highways) gives, at 6,000 ADT, an accident rate of 0.19 accidents/bridge (assuming a bridge length of 150 ft). Further, specifying ice, snow, or frost conditions, which occur on an average of 3 percent of the year (assuming such conditions are not overly represented in accidents), yields only one icy bridge accident per year for every 175 bridges. Now, the actual involvement is substantially higher; but, the fact remains that the majority of bridges do not experience icy bridge accidents in the short time span of a few years. (For example, 2 years of bridge accident data from seven maintenance divisions in Ohio revealed that only 155 bridges out of a total of 6,305 were involved in accidents under icy and snowy pavement conditions (26 of these bridges had greater than one accident).) Thus, for all practical purposes Y (the number of icy and snow accidents per bridge per year) is an attribute, not a continuous variable with a conditional normal distribution.

In order to further visualize this situation, assume that there is only one independent variable, X, to be considered and that the Y and X are ideally correlated; i.e., all the nonzero Y's occur at one end of the range of X, as shown in the frequency distribution in Figure I-1. The resulting regression line is shown also.

Now, $\overline{Y}$ (mean number of accidents per bridge per year) for the Ohio accident data just referenced is about 0.03. All probability statements about a "bad" bridge (one with a large expected Y) will therefore be poor, because such a Y is very remote from $\overline{Y}$. Of course, there are several X's, not one; on the other hand, Y will not be ideally correlated with the X's.

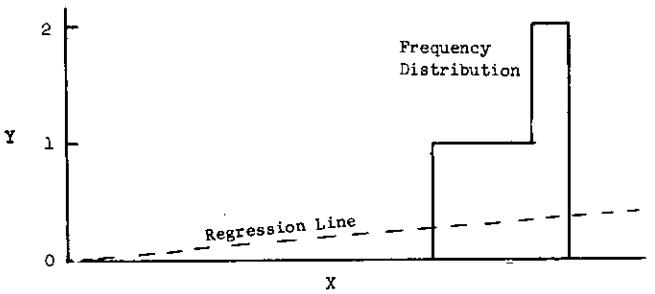

Figure I-1. Illustrative frequency distribution.

The independent variables, X's, used in bridge model development are a mixture of continuous and dichotomous types. (It does no harm to be quantitative.) Creating a scale for a dichotomous X is not reassuring in this case. For example, what two numbers on an "environment" scale are represented by "rural" and "urban"? Obviously, the choice of an artificial scale for such variables will influence the regression function, and there is no good way to know what, if any, scale applies to the data.

Since the response variable and most of the independent variables are attributes, it is appropriate to create categories for the continuous X's and to build a discrete bridge model rather than a continuous one. The bridge model uses available accident statistics and bridge characteristics to estimate the probability of a nonzero number of ice and snow accidents per year for a bridge. This probability is then used to predict the expected number of ice and snow accidents per bridge per year. Data available from 6,305 bridges in the seven maintenance divisions in Ohio were used in developing and subsequently applying the procedure. The data used were:

1. All the bridge accidents on snow or ice, Y, (hereafter referred to as simply accidents) for the 1968-1969 and 1969-1970 winters.
2. Seven characteristics of bridges (The data used for the variables $(X_1, X_2, \ldots, X_7)$ were obtained from reports of highway bridge sufficiency ratings (bridge logs) published at irregular intervals by the Ohio Department of Highways for each division. The data were available for only 7 of the 12 divisions and were published over the period 1967-1970. No attempt was made to update the ADT values to the date

of the accidents, nor was any correction applied to the ADT's for seasonal variation.):

a. ADT (X_1).
b. Over-all length in feet (X_2).
c. Roadway width in feet (X_3).
d. Location—rural (R) or urban (U) (X_4).
e. Structure over water (W) or other (NW) (X_5).
f. Type of highway—divided (D) or undivided (UD) (X_6).
g. Structure type—concrete (C) or other (steel, timber, or stone) (NC) (X_7).

Each bridge is considered as belonging to one of two classes: "good" ($Y = 0$), and "bad" ($Y \geq 1$). All 155 bridges in the seven maintenance divisions with $Y \geq 1$ (the bad bridge population) were tabulated, and a sample of 203 good bridges was selected and tabulated. (The sample size of 203 was sufficient and convenient to obtain from the bridge logs.) The good bridge sample was selected proportionately; i.e., if a maintenance division contained 20 percent of all bridges, then 20 percent of the good bridge sample was taken from that division, etc. Thus, the bridge population of the portion of Ohio for which data were available was fairly represented.

Next, an estimator of the probability that a bridge has greater than zero accidents, given the values of its seven variables, is constructed; that is, $P_r(Y > 0|X_1 = x_1, \ldots, X_7 = x_7)$ is estimated. (The customary notation of capitals for random variables and lower-case letters for values will be used.) As will be seen, there are no formal reasons why the data could not be used to estimate $P_r(Y = i|X_1 = x_1, \ldots, X_7 = x_7)$ for all (integer) values of i. However, the number of bridges in the sample with more than one accident is so small (26) that the estimates would be unreliable. Therefore, only the probabilities of zero and "not-zero" bridge accidents will be estimated directly by the bridge model. The expected number of accidents per bridge, λ, will be estimated under the usual Poisson assumption; that is, it is supposed that the number of accidents per bridge is distributed according to the Poisson assumption:

$$1 - P_r(Y > 0|X_1 = x_1, \ldots, X_7 = x_7) = \frac{e^{-\lambda}(\lambda)^0}{0!}$$

The bridge model is essentially constructed from Bayes' Rule, which states that:

$$P_r(B_r|A) = \frac{P(B_r) \cdot P(A|B_r)}{\sum_{i=1}^{n} P(B_i) \cdot P(A|B_i)}$$

where $B_1, B_2, \ldots, B_r$ constitute any partition of the sample space, $P(B_i) \neq 0$ for every i, and $P(A) \neq 0$. In other words, the conditional probability of B_r, given A, is known if all the "reverse" conditional probabilities and all the unconditional B probabilities are known. The probabilities in the standard form of Bayes' Rule are interpreted in terms of the previous notation as follows:

$$P_r(B_r|A) = P_r(Y > 0|X_1 = x_1, \ldots, X_7 = x_7)$$
$$P(B_r) = P(Y > 0)$$
$$P(A|B_r) = P(X_1 = x_1, \ldots, X_7 = x_7|Y > 0)$$

and

$$\sum_{i=1}^{n} P(B_i) \cdot P(A|B_i) = P(Y = 0)P(X_1 = x_1, \ldots, X_7 = x_7|Y = 0) + P(Y > 0)P(X_1 = x_1, \ldots, X_7 = x_7|Y > 0)$$

For simplicity, assume temporarily that only one bridge variable, X_i, is necessary to predict accidents and that X_i has category numbers $j = 1, 2, \ldots k$. It is desired to estimate $P_r(Y > 0|X_i = j)$ for every j, and according to Bayes' Rule this probability is given by:

$$P_r(Y > 0|X_i = j) = \frac{P(Y > 0) \cdot P(X_i = j|Y > 0)}{P(Y = 0)P(X_i = j|Y = 0) + P(Y > 0)P(X_i = j|Y > 0)}$$

It is easy to estimate $P_r(Y > 0|X_i = j)$ for any of the seven bridge characteristics from the sample of "bad" bridges once the categories for the X's are chosen. The variables X_4 through X_7 are already physically divided into two distinct categories. The variables X_1 through X_3 are not dichotomous and therefore not directly amenable to Bayes' Rule. To illustrate the model development, categories of these three variables (ADT, length, and width) are created by dividing them into five equal sized categories; i.e., the boundary lines are the 20th percentiles from the good bridge distribution. (It is probably wise not to make many more categories than this because of the constraint of only 155 bad bridges.) For example, all ADT's greater than 45,500 are $X_1 = 5$'s, because 45,500 is the 80th percentile of the good bridge population. However, 38.1 percent of the bad bridges have an ADT greater than 45,500. Thus, $P_r(X_1 = 5|Y = 0) = 0.2$, and $P_r(X_1 = 5|Y > 0) = 0.381$. A complete set of these probabilities, along with their respective categories, is given in Table I-1. From the total bridge population it is known that

$$P(Y = 0) = 6{,}150/6{,}305 = 0.9754$$
$$P(Y > 0) = 155/6{,}305 = 0.0246$$

The conditional probability of zero or greater than zero accidents for any given value of any bridge variable can now be computed using the values for $P(Y = 0)$ and $P(Y > 0)$ and the entries in Table I-1. The estimated number of accidents, λ, can then be computed from the conditional probability as discussed previously.

To illustrate the computation of $P_r(Y > 0|X_i = j)$ for a particular bridge, consider the single parameter, type of highway. This independent variable has two category levels: undivided (UD) and divided (D). From the random sample of all Ohio bridges $P(\text{UD})|Y = 0) = 0.842$; and from the universe of "bad" bridges, it is determined that $P(\text{UD})|Y > 0) = 0.645$ (see Table I-1). By applying Bayes' Rule and remembering that $P(Y > 0) = 0.0246$, the probability that an undivided bridge has greater than zero accidents under ice and snow is computed as:

$$P_r(Y > 0|\text{UD}) = \frac{(0.0246)(0.645)}{(0.9754)(0.842) + (0.0246)(0.645)} = 0.019$$

It appears that an undivided highway type is a good trait for a bridge to have, because the probability of greater than zero accidents on such a bridge is only 0.019 compared to

TABLE I-1

TABULATION OF $P_r(X_i = j|Y = 0)$ AND $P_r(X_i = j|Y > 0)$ FOR SEVEN BRIDGE VARIABLES

	Category, j	$P_r(X_i = j\|Y = 0)$	$P_r(X_i = j\|Y > 0)$
X_1 (ADT)			
≤ 4,300	1	0.2	0.039
4,400-9,900	2	0.2	0.103
10,000-20,200	3	0.2	0.174
20,300-45,400	4	0.2	0.303
≥ 45,400	5	0.2	0.381
X_2 (Length)			
≤ 18	1	0.2	0.029
19-28	2	0.2	0.097
29-62	3	0.2	0.097
63-125	4	0.2	0.193
≥ 126	5	0.2	0.594
X_3 (Width)			
≤ 24.0	1	0.2	0.200
24.1-27.9	2	0.2	0.097
28.0-33.0	3	0.2	0.277
33.1-40.0	4	0.2	0.290
≥ 40.1	5	0.2	0.136
X_4 (Location)			
Rural (R)	1	0.837	0.981
Urban (U)	2	0.163	0.019
X_5 (Type of Crossing)			
Over Water (W)	1	0.892	0.587
Other (NW)	2	0.108	0.413
X_6 (Type of Highway)			
Undivided (UD)	1	0.842	0.645
Divided (D)	2	0.158	0.355
X_7 (Type of Structure)			
Concrete (C)	1	0.616	0.290
Other (NC)	2	0.384	0.710

0.0246 for all bridges in general. The reasons for this are not completely clear. However, the difference might result from drivers being more aware of the constant potential hazard of two-way bridges, especially during slippery pavement conditions. The only possible error in the foregoing calculations is sampling error; there are no distributional assumptions to be met.

Broadly speaking, for the regions of Ohio included in Table I-1, it is unfavorable for a bridge to carry a large ADT; to be long; to be in a rural area; to not be crossing a river; to be on a divided highway; and to be constructed of steel, timber, or stone. The influence of bridge width is not clear.

Next, provision must be made for estimating the probability of greater than zero accidents given the *set* of seven values per bridge. This is accomplished by assuming independence for the X_i's; that is, it is assumed that

$$P(X_1 = i, \ldots, X_7 = j|Y = 0) = P(X_1 = j|Y = 0) \ldots P(X_7 = j|Y = 0)$$

and

$$P(X_1 = i, \ldots, X_7 = j|Y > 0) = P(X_1 = i|Y > 0) \ldots P(X_7 = j|Y > 0)$$

Of course, it is ideal to avoid the assumption of independence, but to do so would require an analytical description of all the dependencies among the X's. This is certainly not available from anything less than a rather huge data set, if available at all. The independence assumption is exactly equivalent to the additivity assumption used in multiple standard regression analyses.

Table I-1 can now be used to estimate the probability of greater than zero accidents per year under ice and snow for any bridge, given the values of the seven bridge variables. For example, suppose a bridge has the following characteristics:

Parameter	*Value or Designation*	*Category*
ADT	50,000	5
Length	150	5
Width	34	4
Location	Rural	1
Type of Crossing	Not Over Water	2
Type of Highway	Divided	2
Type of Bridge	Nonconcrete	2

Applying Bayes' Rule:

$$P_r(Y > 0|X_1 = 5, X_2 = 5, X_3 = 4, X_4 = 1, X_5 = 2, X_6 = 2, X_7 = 2)$$

$$= \frac{(.0246)(.381)(.594)(.29)(.355)(.413)(.710)(.981)}{[(.0246)(.381)(.594)(.29)(.355)(.413)(.710)(.981) + (.9754)(.2)(.2)(.2)(.158)(.108)(.384)(.837)]}$$

$$= 0.794$$

Such a bridge has about four to one odds of having one or more ice and snow accidents in a year. This represents quite an increase over the general bridge population where

$$P_r(Y > 0) = 0.0246.$$

To compute the expected number of accidents per year on the example bridge, the Poisson assumption can be used:

$$(1 - 0.794) = \frac{e^{-\lambda}(\lambda)^0}{0!}$$

$$\lambda \simeq 1.6$$

Thus, this bridge can expect 1.6 ice and snow accidents per year on the average.

The question naturally arises on the number of variables necessary to produce a satisfactory bridge model. The variables ADT and length are so strongly correlated with accidents that it is certainly unreasonable not to include them in any bridge model. With the amount of data available at this time, ADT and length alone are obviously insufficient to yield much scope to a bridge model, since there are only 25 ADT-length combinations. Another reason for desiring several variables is the possibility of "averaging out" the interrelationships among X's; i.e., reducing as much as possible the departures from the assumed independence of the X's.

There is some information regarding these questions. At one time X_1, X_2, X_3 were divided into 10 categories each (rather than five). With 10 categories, the maximum $P_r(Y > 0|\{X_i = i\})$ was about 92 percent, compared to about 80 percent under the present bridge model. It is reasonable to want the maximum $P_r(Y > 0|\{X_i = i\})$ to be "almost" 100 percent and the minimum $P_r(Y > 0|\{X_i = i\})$ to be virtually zero. Thus, creating only five categories of X_1, X_2, X_3 (necessary because of limited sample size) appears to have a sizable impact on the "power" of the bridge model.

One of the weaker variables, X_6, was deleted from the bridge model when 10 categories were used for the first three variables. This caused the maximum $P_r(Y > 0|\{X_i = i\})$ to drop from 92 percent to about 83 percent. Thus, it appears that the bridge model needs all the variables it now uses, although with more data and thus the ability to accurately define more categories of X_1, X_2, X_3, it might not.

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