NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT **285**

EVALUATING ALTERNATIVE MAINTENANCE STRATEGIES

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
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EVALUATING ALTERNATIVE MAINTENANCE STRATEGIES

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
MAINTENANCE
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NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. JUNE 1986

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.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By Staff
Transportation
Research Board

This report will be of interest to highway maintenance managers concerned with quantifying costs of any strategy for the maintenance of pavements and bridges. Furthermore, it will be of interest to other top management and analysts concerned with allocating funds between maintenance and other activities—rehabilitation and new construction.

Many studies have shown that the nation's pavements and bridges are deteriorating at alarming rates. Because of inflation and limitations on highway agencies funds, maintenance and rehabilitation budgets have not been sufficient to maintain pavements and bridges at satisfactory levels of service. Diminishing resources and escalating needs demand methods to select the best balance between maintenance expenditures, rehabilitation, and new construction. This study addresses a specific facet of this need—development of a method that can be used to evaluate agency and user costs resulting from decisions regarding maintenance service levels and rehabilitation timing.

Life-cycle analysis (based on life-cycle costs) was identified as being an effective method to use for such evaluation. The method is used to compute, for specified maintenance service levels, agency costs, vehicle-operating costs, traffic-interference costs, and other consequences including accidents, lost time, pollution, and inconvenience.

Because maintenance methods and their effectiveness vary with different materials, environments, and practices, the analyst must input cost and effectiveness for each maintenance treatment chosen for evaluation. Although pavement maintenance experiments were conducted in 10 states during the course of the research, only limited data were available at the project conclusion. As the effectiveness for various maintenance treatments become known, the method will become more valuable to highway and road agencies for evaluating any maintenance service level.

CONTENTS

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Bertell C. Butler, Jr., ARE Inc, was the principal investigator. Advisory support was received from Dr. W. Ronald Hudson and Fred N. Finn, co-principal investigators. The work was conducted under the general supervision of Bertell C. Butler, Jr., and R. Frank Carmichael, III, ARE Inc, with assistance from Leonard O. Moser, Systems Analyst, Steve B. Seeds, Research Associate, Pat Flanagan, Research Assistant, Dan S. Halbach and Chang Ren He, programmers, Mark Wilson, Todd McCullough, Terry Dorris and Michael Currin, Technicians, and Dr. Virgil Anderson, Statistical Consultant.

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EVALUATING ALTERNATIVE MAINTENANCE STRATEGIES

SUMMARY

The implied consequences of deferring needed highway maintenance are that untreated maintenance conditions will get worse, and these worsening conditions will be more expensive to correct and will increase the adverse impacts to the public. This study was made to determine the magnitude of these implied increased agency costs and public impacts.

Deferred maintenance is not a quantifiable term nor is it an expression used widely by the highway maintenance community. Rather, highway agencies set various maintenance service levels based on making the best use of available resources. The consequence of delaying or deferring highway maintenance is defined by the difference in agency costs, user and nonuser impacts for two maintenance service levels.

Objectively evaluating maintenance strategies requires that maintenance service levels be quantitatively defined. Highway agencies are reluctant to establish definitive maintenance service levels for fear of creating tort liability. In fact, not setting service level guides can create more liability; therefore, agencies should define objective guides when possible.

Little information could be found that quantifies the effectiveness of different maintenance treatments in slowing the deterioration of a maintenance element. Quantitative information on maintenance effectiveness can be obtained through in-service monitoring of maintenance element conditions and documented histories of maintenance treatments. A limited program of in-service monitoring was initiated during this study to address flexible pavement fatigue cracking. The program is a cooperative effort with ten state agencies where 240 sites were established covering the country's different climatic regions. All states agreed to continue monitoring the sites in their state. These efforts will produce an initial data base which can be used to improve the methodology developed to evaluate the consequences of setting different maintenance service levels for flexible pavements.

Life-cycle costs were identified as being an effective method to use in evaluating agency costs and public impacts for given maintenance service levels. A methodology was created that computes for specified maintenance service levels: agency costs, vehicle operating costs, traffic interference costs, and other consequences including accidents, lost time, pollution, and inconvenience. General guides are presented on treatment effectiveness, but the costs and effectiveness of any maintenance treatment are a required exogenous input to the methodology.

The life-cycle period is defined as the years to rehabilitation or reconstruction. All agency expenditures and user costs are converted to constant dollars (present worth), summarized for the entire period and then annualized using a capital recovery factor to permit direct comparison for different analysis periods. The consequences of reducing maintenance are defined as the difference in costs and impacts between a reference maintenance service level and some lower level.

The methodology created permits maintenance managers to quantify the agency costs and public consequences of pursuing any maintenance strategy. Since state

maintenance organizations exhibited a definite lack of enthusiasm to base funding decisions on user costs, agency costs were intentionally separated from user costs. This provides highway engineers with the ability to examine the effect of different strategy options on either agency costs or user costs separately.

The evaluation procedures can be used to establish criteria on the effectiveness and costs of treatments that justify funding. Alternatively, administrators can question funds earmarked for treatments not meeting such criteria.

This work builds on work reported in *NCHRP Report 223.* That methodology can be used to optimize relative weights of the value of maintenance to preserve investment versus that intended for other purposes. Once this determination has been made, the programs created in this project can be used as a tool to explore the relative merits of different maintenance service levels.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

INTRODUCTION

Although vehicle registration exceeds 160 million and vehicle-miles of travel continue to increase, resources available to construct and maintain U.S. roads are on the decline. Highway agencies are losing purchasing power because of inflation and a simultaneous reduction in gasoline-tax revenues. The revenue decrease is due to lower fuel consumption arising from the increasing use of lighter and more fuel efficient vehicles. Light passenger vehicles currently represent about 40 percent of the passenger-car population. They are steadily increasing in number and are expected to represent almost 90 percent of the passenger-car population by the turn of the century. Vehicle gasoline economy has increased steadily since 1976 going from an average 12.2 to 14.3 miles per gallon, a 17 percent increase (*1*). Improvements in fuel economy are expected to continue.

The higher labor, equipment, and material costs associated with continued inflation with no commensurate increase in revenue have caused highway agencies to reduce personnel and cut back on expenditures at all levels. Between 1978 and 1982, constant dollar expenditures for roadway maintenance on the state-administered highway system fell from $3,000 to $2,200 per mile (*1*). The impact of these reductions is compounded by increasing maintenance workloads created by an aging system and the users' growing expectations for higher levels of service. In many highway agencies, the reduction in purchasing power means that highway and bridge maintenance programs are being cut when they need to be increased. For example, the amount of Interstate pavement falling below a psi of 2.3 is doubling every 3 years (*1*). Also, in its most recent report to Congress on the Highway Bridge Replacement and Rehabilitation Program, the U.S. Department of Transportation reported that almost 24 percent, or more than 135,000, of the nation's bridges are structurally deficient (*2*).

To reverse such trends, financial resources must be made available to highway agencies. To get these resources, highway administrators must show the consequences of poor roads to those responsible for distributing public funds.

Diminishing resources demand methods to select the best balance between maintenance expenditures and maintenance service levels. This study addresses a specific facet of this need, i.e., a methodology that can be used to evaluate the consequences to a highway agency and the public of delaying needed highway maintenance.

OBJECTIVES

The study objective was to develop procedures, guidelines, and criteria for state highway agencies to use in determining alternative maintenance strategies (involving timing and practice) for highway pavements and bridges. The results were to have application by highway agencies for (1) budget preparation and financial planning, (2) discussions with legislatures and local governments, (3) maintenance work program preparation, (4) use in maintenance management systems, and (5) work prioritization and assignment. To achieve these results, it was necessary to investigate fully the consequences of alternative maintenance strategies over the life cycle of a highway pavement or bridge in terms of costs to highway agencies, highway users, and other parties.

A Phase I Interim Report (*3*) presented background information on the consequences of deferring maintenance activities and provided a framework for the evaluation of such consequences. It was based on an assessment of current literature and evaluation of practices by eight state highway agencies. The Phase II study objectives were:

1. To gather secondary and, if necessary, primary data describing changes in: (a) the deterioration of pavements and bridges arising from a range of maintenance strategies and varying climatic or regional conditions over the life cycles of such facilities; (b) user costs including safety; (c) the environment; (d) the economy; and (e) the impacts to the nonuser.
2. To develop specific cost models to evaluate the effects of different maintenance service levels on pavement and bridge life-cycle costs.
3. To quantify the user costs associated with the condition of pavements and bridges.
4. To evaluate the impacts of maintenance service levels on various nonuser considerations.
5. To adopt or develop a methodology for evaluating different maintenance service levels.
6. To provide "real world" example applications of the method for pavements and bridges. The intent was to illustrate the method for use by state highway agencies.

STUDY SCOPE

The study addressed alternative levels of maintenance. Maintenance was defined as activities that slowed the deterioration of pavements and bridges. Rehabilitation and reconstruction were not considered maintenance; however, all factors influencing the life-cycle costs of pavements and bridges were included. Therefore, to the extent that rehabilitation is delayed or its extent altered by different maintenance policies, it was to be a part of the life-cycle analysis procedure.

RESEARCH APPROACH

Model Development

The influence of maintenance on pavement and bridge life-cycle costs depends on (1) how a maintenance treatment alters existing conditions, and (2) how extensively a maintenance treatment slows the deterioration process. The literature search revealed little quantitative information on these two issues.

Preliminary correspondence with the 40 state highway agencies not contacted in Phase I generated numerous offers of cooperation and the indication that data were available that could be useful in establishing the influence of maintenance on pavement and bridge conditions and performance. The states offering cooperation are shown in Figure 1.

The information needed to satisfy the above-stated methodology requirements was to be obtained from state highway agencies. Data were sought that would quantify a maintenance treatment's effectiveness in correcting existing conditions, extending serviceability, and increasing structural life. The data that would answer this need fell into four categories:

1. What was done—This refers to the maintenance or rehabilitation treatment that was executed in response to a maintenance condition.
2. Where it was done—This identifies the specific bridge or pavement location where the treatment was executed.
3. Why it was done—This measures the severity of the maintenance condition that generated a treatment response.
4. When it was done—This is the date when the treatment was executed and helps determine conditions at the time work was executed.

Three options were pursued in visits with the states to establish this information:

1. Find documented histories of maintenance expenditures

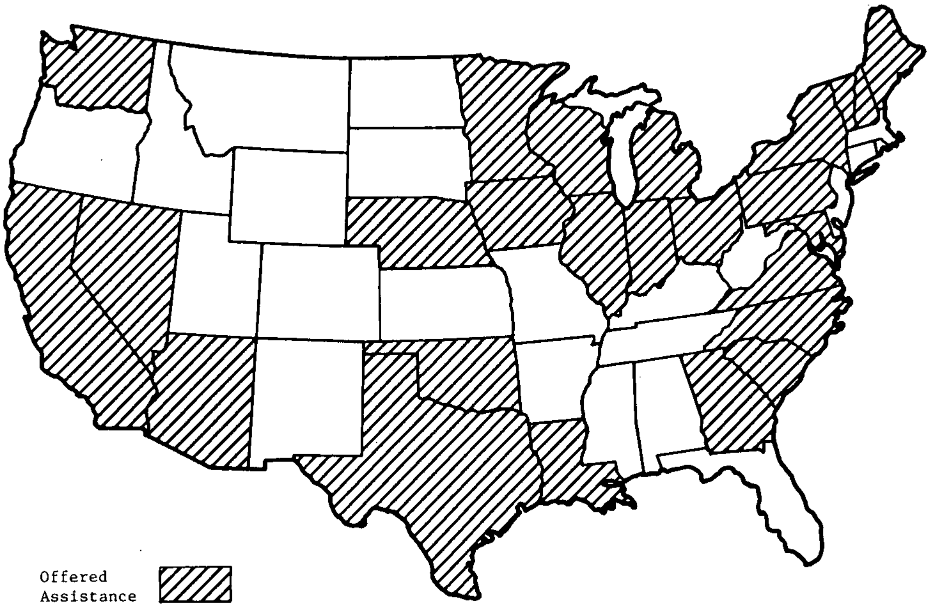


Figure 1. States contacted that offered to provide assistance to study.

by specific pavement or bridge activity and by specific pavement location or bridge, and corresponding documentation on the condition of the pavement and bridge over time.

2. Find documented histories of maintenance expenditures by specific pavement or bridge activity and by specific pavement location or bridge plus established quantitative maintenance levels. These levels would define the condition of the pavement or bridge at the time a maintenance treatment was executed.

3. Establish test locations where maintenance is imminent, evaluate the maintenance condition severity, and monitor future conditions to identify the influence of different maintenance treatments and timing on pavement performance.

The first two options were expected to produce information that would permit establishing the influence of maintenance and maintenance levels on maintenance element performance. The key points in establishing this data collection effort were the need to define *what* was done to the element, *when* it was done, and *how* the element performed following maintenance and rehabilitation. Also extremely important was the condition of the element prior to the activity and the extent of the activity. Without information on these factors, it was not considered possible to effectively establish equations to predict future conditions as a function of maintenance levels.

The states indicating an interest in providing informational input to the study were personally contacted and discussions held with their planning, research, and maintenance personnel. In these meetings with the states, it was possible to detail specific informational needs. These needs could not be met in most states. Where states had information, it covered only a limited portion of their highway network. Also, the level of detail varied, particularly as related to pavements and bridges, so separate approaches were outlined to evaluate the consequences of deferred maintenance on pavement and bridges.

Also sought during these state visits were guides on the type of methodology and presentation format that would maximize the probability that study results would be used by the states.

Pavements

Pavement life-cycle costs methodologies are fairly well defined. They involve simulating or modeling the performance of a pavement for a specified number of years exposed to a given set of factors including: (1) a specific environment, (2) forecasted traffic, (3) select maintenance treatments, and (4) alternative rehabilitation timing.

Total agency costs and user impacts are quantified for any combination of the foregoing.

The simulation process depends on a number of different cause and effect relationships that are defined by mathematical equations. These equations have two outcomes. First, they predict the future condition of a specified pavement. Second, they quantify user impacts resulting from user exposure to the predicted condition.

Equations that predict pavement condition are termed damage functions. Considerable work has been done and is continuing on improving the quality, responsiveness, and credibility of damage functions. However, they do not account for the effect of varying maintenance treatments and service levels on pavement performance.

The user impacts that have been quantified in life-cycle analyses include vehicle operating costs, accidents, travel time, and pollution emissions. Pavement conditions affect these impacts. Pavement roughness accelerates the deterioration of vehicles, resulting in increased vehicle maintenance, repair, and depreciation. Pot holes or blowups create hazards and increase the risk of accidents. Obstructions cause vehicle avoidance maneuvers leading to accidents and increases in vehicle operating costs. Smooth pavements become slippery when wet and contribute to accidents. Distressed pavement can influence vehicle behavior, i.e., speeds, speed changes, or lane changes, which can increase vehicle operating costs.

Life-cycle cost (LCC) models also include an evaluation of the impacts (e.g., delays) to road users resulting from the occupancy of the pavement by maintenance crews to repair, restore, resurface, or rehabilitate the pavement.

The LCC analysis is a blend of user inputs and predefined cause and effect relationships. The user specifies the characteristics of the pavement (existing or designed). This includes layer thicknesses and moduli, subgrade characterization, and pavement age. The required environmental inputs depend on the variables included in the damage functions. Traffic is defined by vehicle type and trip purpose, and the user designates the volume distribution and expected growth of this traffic. Also input are appropriate unit costs to be used in calculating construction, maintenance, rehabilitation, and user costs. Finally, the LCC analysis requires that maintenance treatments and rehabilitation strategies be specified.

The LCC analysis uses the inputs to simulate the pavement's exposure to traffic and environmental factors annually. The resulting pavement performance is predicted in terms of a series of conditions. These conditions are quantified using the damage functions. The specified maintenance treatment is simulated to correct, modify, or eliminate the predicted conditions. The maintenance treatment is costed, and the pavement condition to which traffic is exposed is determined. User impacts are determined and costed where appropriate. The rehabilitation strategy that has been designated is executed as necessary. The influence on traffic of road occupancy for maintenance or other activities is estimated, and the resulting user impacts are calculated and costed.

The LCC analysis evaluates inputs and costs through a number of years, discounts the costs to a base year period, annualizes these costs, and generates an output report. A run is made for each strategy being evaluated. The process can be used in an optimization routine to treat a network of roads and prioritize maintenance or rehabilitation programs.

Because the life-cycle methodology is well developed, an existing life-cycle model was modified to satisfy project needs. The model selected was EAROMAR (*4,5*). Data were needed that could be used to modify and improve the EAROMAR pavement damage models to account for different maintenance treatments and service levels. It was also required to develop current information on maintenance, rehabilitation, user costs, and nonuser impacts.

The pavement performance data needed to modify and improve the damage models can be obtained from long-term pavement condition monitoring. The highway agencies contacted had pavement management systems ongoing or under development. Some states had accumulated a pavement condition history, but they generally had no correlatable maintenance treatment data. Without both condition and maintenance data, it is not possible to relate maintenance service levels to pavement performance.

The researchers recognized that establishing test locations along the lines suggested in option 3 would not provide the historical data required for an effective analysis of pavement performance following maintenance activities now. However, without this data base, the problem under study can never be adequately addressed. Therefore, it was felt that a valuable output from this study would be the initiation of this required data base.

Most of the states that were visited offered to cooperate in establishing test pavements that could be monitored to develop the data base required to evaluate the effectiveness of different maintenance treatments and timing on future pavement performance. The research team felt that any state willing to finance such an effort would be interested in continuing it and, therefore, would be generating data for future use. Further, because such studies would be in a state's self-interest, it would be handled by the state and was not expected to require a large investment of project resources.

Inasmuch as resources were limited, the effort was restricted to one pavement type, and primarily, one distress. Selected for study were asphaltic concrete pavements and fatigue cracking. Ten states, covering the Thornthwaite environment zones, were included, and 24 sections were sought in each state. The criteria used to select sections included: (1) the ability to characterize the existing pavement, (2) filling the design factorial shown in Figure 2, and (3) the pavement needed to exhibit fatigue distress.

The researchers worked directly with each state to select and map the fatigue distress present in each section. The selection and mapping procedures are described in Appendix A where a location map, cracking map, and the characterization information collected for each section are illustrated.

Bridges

The state visits revealed that the only information available on bridge conditions was the FHWA structure inventory and appraisal (SI&A) data base.

Since a methodology was needed that would evaluate alternative maintenance strategies for bridges, predict the conditional state of bridge distresses as a function of various maintenance activities over the bridge life, and translate these relationships into bridge life-cycle costs, the research team proposed to construct a methodology using the FHWA structure inventory and appraisal data because these data are collected by all states at least biennially for each structure on state-administered systems. The data include condition appraisal and other information (e.g., type of structure, age, location, ADT) relevant to an examination of different maintenance activities.

The approach was to explore the relationship between maintenance activities (e.g., painting and cleaning cycles) and bridge condition (estimated remaining life, condition ratings, operating rating) using the available 8-year history. The research would focus on a predominant bridge type because an examination of related research efforts in New York and North Carolina suggested that it is virtually impossible to identify a single set of relationships which can realistically predict life-cycle costs for a dozen or more different bridge types. Maintenance activity data obtained from discussions with state officials concerning maintenance policies and practices and bridge maintenance files were planned to be used to draw conclusions about the effect of different maintenance approaches on the life cycle of bridges, thereby providing the basis for developing life-cycle cost estimates for each maintenance approach.

	SUBGRADE	
TRAFFIC	GOOD	POOR
HIGH		
LOW		

Figure 2. Flexible pavement, fatigue cracking, design factorial.

A relationship was established with the North Carolina DOT to gain access to their SI&A data base and their maintenance history data base. North Carolina was selected because it maintains two data bases with detailed records on some 17,000 state-maintained structures. One file contains information on past bridge maintenance expenditures disaggregated by type of work activity (e.g., maintenance of steel expansion joint devices). The other is an expanded version of the FHWA structure inventory and appraisal data file.

Agency Life-Cycle Costs Information

Agency costs include various maintenance and rehabilitation activities. Most state highway agencies have some form of maintenance performance standard. Although they are called by various names, including operational guides, maintenance standards, work method statements, or just plain standards, they generally describe for a specific maintenance activity the labor, equipment, and materials required; the procedures to follow in performing the work; and an estimated production rate that can be achieved. The approach used in this study was to collect performance standards from the states that were contacted and develop consensus standards for representative maintenance work. These consensus standards would be expanded using current labor, equipment, and material unit costs. Also planned during state contacts was the collection of contractor bid price information on rehabilitation activities. Performance standards define the work or accomplishment units that are associated with a given maintenance activity. They vary widely and, therefore, the research team planned to define specific units so that these units would be compatible with the distress predicted by the damage models in the methodology being developed.

Maintenance Service Levels

To facilitate communication during the conduct of the project, a number of terms were defined. These are listed in Table 1. Of particular concern to many U.S. State Highway Departments was the term "deferred maintenance." As may be noted from the table, this term is defined as a reduction in maintenance service levels.

Highway agencies have been reluctant to quantify maintenance service levels because they recognize and contend that such guides specify a standard of conduct that may be used

Table 1. Glossary of terms.

Maintenance Element:	A part of the highway infrastructure that has a maintenance condition that can be corrected or repaired through highway maintenance (e.g., asphalt concrete pavement, Portland cement concrete bridge deck, Portland cement concrete bridge pier, or structural steel).
Maintenance Condition:	A manifestation of distress, deficiency or other undesirable characteristics of maintenance elements that can be corrected or repaired through highway maintenance activities (e.g., pavement rutting or cracking, shoulder drop off, bridge steel corrosion or dirty scuppers).
Considerations:	Areas of concern which are affected by the severity of the individual maintenance conditions which exist (e.g., agency costs, user costs, safety, non user impacts, riding comfort, aesthetics, etc.).
Threshold Condition:	The limiting value or severity of a maintenance condition that will activate a maintenance activity.
Maintenance Service Level:	The resulting average severity of a maintenance condition due to performing highway maintenance to attain the planned serviceability for the facility over its design life with projected traffic volumes.
Deferred Maintenance:	A reduction in a planned maintenance service level.
Present Serviceability Index (psi):	A number derived by formula for estimating the serviceability rating from measurements of certain physical features of the pavement.
Serviceability:	The ability at time of observation of a pavement to serve high-speed, high-volume automobile and truck traffic.
Maintenance Activity:	A type of work that can be performed by maintenance field crews or contract maintenance in preventing, correcting or repairing a maintenance condition.
Maintenance Treatment:	A specific combination of labor, equipment, materials and procedures used to perform a maintenance activity.
Functional Deterioration:	Reduction in the serviceability of a maintenance element.
Demand Maintenance:	Corrective maintenance to eliminate distress that can adversely affect traffic flow or safety.
Rehabilitation:	Maintenance or construction that restores the functional usefulness of a physical element of the highway infrastructure.
Preventive Maintenance:	Treatments undertaken to correct or slow the evolution of maintenance conditions before they threaten capital investment or endanger road safety.
Structural Deterioration:	A reduction in the structural integrity of a physical element of the highway infrastructure.

against them in tort liability cases. With the erosion of sovereign immunity, tort liability litigation has been steadily increasing and highway agencies do not want to assist litigants by establishing standards of care that define negligence per se on the part of the agency. Therefore, maintenance service levels are not rigidly defined because of the fear that written guides will be used against them in court (*6*). This is unquestionably true, inasmuch as one of the strongest types of evidence that can be brought into court during tort litigation is the agency's own guidelines and policies. However, this is not as important as it first appears. If the agency is negligent, they will in all probability lose a tort case regardless of available documentation.

When a highway agency does not define its own maintenance service levels, the courts will define them. The courts will not have all of the facts and will not be able to give due consideration to competing priorities that would be considered by the highway agency. That simply means that the agency cannot ignore the problem, but should take steps to define levels of service that are consistent with the constraints under which they are forced to operate. As stated by Thomas in *NCHRP Research Results Digest 80,* "[t]he primary defense to tort liability . . . is based on the theory that certain action taken by government is 'discretionary' and, therefore, immune." (*7*). An official exercising discretionary functions or duties is immune from liability. The term discretionary refers to the power and duty to make a choice among valid alternatives, considering the alternatives and making judgments to come to a decision or choose a course of action. However, an individual engaged in the exercise of nondiscretionary, ministerial duties could be held liable for the consequences of his negligence. Ministerial duties involve clearly defined tasks not permitting discretionary action. An outgrowth of this concept is that the defense of insufficient funds will be held irrelevant unless the agency can show a formalized program to eliminate deficiencies and show that they are diligently following this program. This program, of course, should be based on an assessment of a number of considerations including accident risks, cost effectiveness, budget restraints, and formal project prioritization and programming procedures.

The following action guideline for minimizing tort liability was presented in a recent TRB publication (*6*): "Establish maintenance levels of service and ensure that work is performed in accordance with them."

Once levels of service have been established, they must be rigorously followed. Thomas discusses the liability of State Highway Departments for Maintenance defects in *NCHRP Research Results Digest 80.* As established in *Indian Towing Co. v. United States* (*8*) and *State v. Abbot* (*9*), once the initial policy determination to maintain the highway safety is made, the state is not given the discretion to do so negligently.

Agencies might first believe that following this recommendation is tantamount to "jumping from the frying pan into the fire." However, the recommendation is based on the following reasoning. No matter what the agency does to provide safe conditions for the road user, accidents will occur. Attempts will be made to show that the agency was negligent since there are always methods to increase safety. This is undoubtedly true, but only at the expense of not doing something else. Therefore, it is of paramount importance that the agency be able to demonstrate that its conduct was based on a rational evaluation process. This process should include consideration of a range of alternatives and an evaluation of the impact of each alternative on user mobility, convenience, economy, protection of the environment, and safety. A reasonable balance needs to be demonstrated between safety and other system needs. Finally, the results of the process need to be defined and documented in a manner understandable to the public. The implementation process should allocate available resources based on a plan that defines a prioritized schedule. This process requires that maintenance service levels be defined in quantitative terms.

A distinction needs to be made between a maintenance service level and the conditions that cause a highway agency to execute a maintenance response. As the term implies, maintenance service levels provide a level of service to the road user or a level of structural integrity to the maintenance element that is treated. For the road user, this is the usefulness of the maintenance element in providing service, i.e., pavement riding quality or the absence of holes and other deterrents to safe use of the pavement. The measure of the usefulness is the average ride quality over a specified road surface and interval of time, or the probability of not encountering an unsafe condition on the same surface over the same period. Relative to structural integrity, maintenance organizations are concerned with their ability to retard maintenance element deterioration, thereby delaying and possibly reducing future rehabilitation needs.

In both cases, maintenance is performed to achieve some level of future performance that influences the user's comfort, convenience, and safety or the timing and extent of agency rehabilitation. In either case, the maintenance service level is the resulting condition of the maintenance element being treated over time.

Since a maintenance service level is a changing condition over time, it is not definable. What is definable is the condition of the maintenance element at different points in time. By specifying the condition that will activate a maintenance response, one can control in an average sense, the maintenance service level achieved. This is defined as the threshold condition that will activate a maintenance response.

CHAPTER TWO

FINDINGS

Study findings reflect the methodologies developed to evaluate alternative levels of maintenance. Pavement and bridge agency costs methodologies were developed separately. This accommodated the different data bases available to support each. The routines that evaluate impacts apply to both pavements and bridges.

METHODOLOGY CRITERIA

The project objective was to produce easily understandable and implementable guides—criteria and procedures to be used by state highway agencies for determining the consequences of setting different maintenance levels in the process of selecting a maintenance strategy for their state.

The project staff met with numerous highway maintenance personnel during the study, and tried to determine how to present the study results to meet this objective. The researchers sought criteria to guide them as they developed the required methodology and the final project report. For the study results to be implemented, they needed to be both credible and simple. It was determined that credible meant the following:

1. The study results must be usable by any highway agency. The methodology should not be based on the state experiences where assumptions concerning procedures, material performance, or costs could invalidate guides or criteria.
2. The methodology should focus on determining agency costs rather than user impacts although the latter were of interest.
3. The methodology should not be hidden in a "black box."

Simplicity of the methodology was identified as being a key to achieving implementation. The complexity and level of detail required by many procedures and computer programs discourages their use by state highway agencies. Furthermore, to have maximum value, the procedures need to be suitable for use at district levels as well as headquarters. Emphasis was placed on:

1. Being able to use the methodology piecemeal, i.e., becoming familiar in a short time with one part of the methodology, demonstrating its usefulness, and then moving on to other parts.
2. Recognizing that the first users will be expected to learn and demonstrate the viability of new procedures for their maintenance organizations.
3. Recognizing that programming for microcomputers is easier to use. Access to mainframes usually involves long turnarounds and excessive expense. Also, microcomputers are becoming available at all organization levels, i.e., districts and residences.

Most importantly, it was established that highway agencies reference to "deferring" maintenance is a misnomer. Reduced funds may require that lower service levels be programmed. As long as these programs are met, maintenance is not deferred.

The term "deferring" implies that there is some normal level that has been reduced. There are no normal levels, so it is necessary to evaluate different maintenance levels, and define *deferred maintenance* as the difference between two maintenance levels. Different maintenance level results are quantified by specifying the threshold condition of the maintainable element that triggers maintenance or the frequency that a maintenance activity is performed.

The strategies evaluated consist of different combinations of maintenance activities performed at different times or for different conditions. What are evaluated are agency costs and user impacts.

METHODOLOGY IMPLICATIONS

The methodology described in this report provides highway agencies with a process that can be used to evaluate maintenance service levels. Furthermore, the methodology addresses the project objective because:

1. Deferred maintenance is a relative term and one must have a reference service level before differences can be evaluated.
2. The consequences of any service level are evaluated in terms of both agency cost and public consequences.
3. Any reference maintenance service level can be specified and the consequences of any lesser level is simply the difference in consequences between the two levels.

It was established that two factors were important to the life-cycle methodology that was adopted to evaluate maintenance strategies. First, it was necessary to quantify the improvement in conditions resulting from a maintenance response because it is the pavement condition that impacts on the road user. This is illustrated in Figure 3 where four condition levels of improvement are shown. The second was to predict the subsequent performance of a maintainable element following a specific maintenance treatment because this determines how soon the pavement must be rehabilitated. This is illustrated in Figure 4 where four different deterioration rates are shown.

Consider pavement conditions. It is necessary to know the conditions that have an adverse impact on the road user, the magnitude of that impact, and the extent that the conditions are improved when maintenance is applied.

Pavement conditions impact road users by affecting vehicle performance and driver performance. First, a vehicle's performance is quantified by measuring its rate of consuming fuel and oil, tires, and the rate that it wears out, i.e., generates the need for repairs and depreciates. These performance parameters are affected by road roughness and vehicle speed and acceleration and deceleration patterns. Therefore, to the extent that pavements are rough and pavement conditions affect driver behavior, vehicle performance is altered and, therefore, impacts are changed.

Driver performance (or behavior) is quantified by measuring vehicle speed, speed variance, headways, avoidance maneuvers, brake applications, and lane changes. Driver performance is affected to the extent that pavement conditions affect these parameters.

Finally, some pavement conditions may be hazardous and affect driver safety. These conditions are slipperiness, obstructions, or holes that encourage driver avoidance maneuvers or loss of control, and conditions that distract the driver from his driving task.

A large number of pavement distresses have been associated with pavement surface conditions. Also, the distress types are related to the type of pavement being examined, i.e., asphalt, concrete, or composite. Concrete can be further divided into plain, reinforced, and continuously reinforced; and each pavement type exhibits its own range of unique distresses. Typical pavement distresses are given in Table 2.

The distress conditions in Table 2 were examined for their potential influence on either vehicle performance or driver performance. They can all be reduced to three pavement characteristics which are: (1) roughness, (2) slipperiness, and (3) obstructions (physical and visual). An assessment was made of the contribution of each distress to the three pavement characteristics based on expected magnitude of the influence. A ten-point scale was used with ten being a maximum influence. Based on this subjective scaling, pavement blow-ups have the maximum adverse effect (mostly safety-related). However, they are rare events and highway departments, in recognition of the adverse consequence of blow-ups, take immediate steps to correct them. Therefore, although severe in impact, blow-ups are not present for long durations and their impact over a life-cycle evaluation period is minimal.

Next, in order of magnitude, are polished aggregates which contribute to slipperiness but are considered a safety hazard principally during wet weather, i.e., when the pavement is wet.

Faulted joints are third in having an adverse effect and impact principally on road roughness. Fourth on the severity prioritization scale is bleeding (slipperiness), corrugations (roughness), and rutting (safety and roughness). The last ranked are depressions (roughness, slipperiness, and obstruction), and patch deterioration (roughness and obstruction).

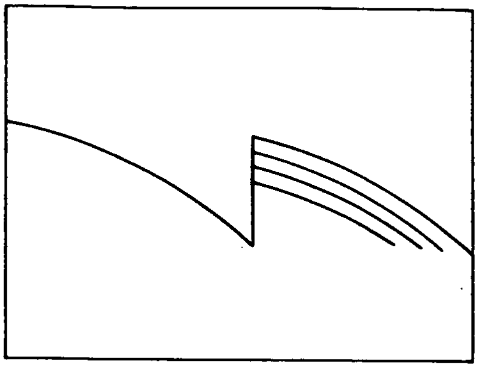


Figure 3. The condition is corrected to different degrees.

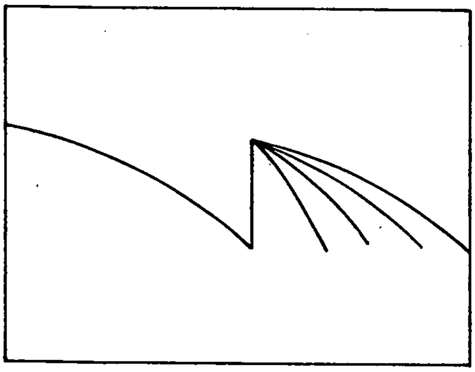


Figure 4. The performance following a treatment may vary.

Based on the in-house, subjective assessment described above of pavement condition on vehicle and driver behavior, it was concluded that the most important variable is roughness, with obstructions second, and slipperiness third.

The three factors, roughness, obstructions, and slipperiness, are the only pavement conditions whose impact on vehicle and driver performance can be evaluated. Therefore, condition is improved only to the extent that a maintenance treatment alters roughness, eliminates obstructions, or corrects slipperiness.

A second concern in establishing the methodology was the need to predict the performance of the maintained element following a maintenance treatment. Figure 4 shows different rates of future deterioration. It is known from a study done in Brazil to relate construction, maintenance, and user costs that the rate depends on both the treatment and the condition of the maintenance elements at the time of the treatment(*10*). These results were confirmed in discussions with state highway personnel. However, the research was unable to find the information or data base that would permit one to quantify this performance as a function of existing condition, maintenance treatment, and the environment. Since such relationships are the key to creating any creditable methodology, a major commitment of project

Table 2. Pavement distress scaled for impact on roughness, slipperiness, and physical and visual obstructions.

	Roughness	Slipperiness	Obstruction Physical	Obstruction Visual	Scaled Total	Rank
ASPHALT SURFACED DISTRESS						
Alligator or Fatigue Cracking	0	0	0	0	0	
Bleeding	0	5	0	3	8	4
Block Cracking	0	0	0	0	0	
Corrugation	5	0	2	1	8	4
Depression	2	3	2	0	7	5
Joint Reflection Cracking from PCC Slab	1	0	0	0	1	
Longitudinal and Transverse Cracking	0	0	0	0		
Patch Deterioration	3	0	3	1	7	5
Polished Aggregate	0	10	0	0	10	2
Potholes	2	0	5	2	9	3
Pumping and Water Bleeding	0	4	0	1	5	
Raveling and Weathering	2	2	0	1	5	
Rutting	3	0	3	2	8	4
Slippage Cracking	1	0	0	0		
Swell	0	0	0	0		
	19	24	15	11		
JOINTED PLAIN CONCRETE DISTRESS						
Blow-up	2	0	10	10	22	1
Corner Break	0	0	0	0		
Depression	2	3	2	0	7	5
Durability ("D") Cracking	0	0	0	0		
Faulting of Transverse Joints and Cracks	8	0	1	0	9	2
Joint Load Transfer System Associated Deterioration	0	0	0	0		
Joint Seal Damage of Transverse Joints	1	0	0	0	1	
Longitudinal Cracks	0	0	0	0		
Longitudinal Joint Faulting	2	0	1	0	3	
Patch Deterioration	3	0	3	1	7	5
Popouts	1	0	0	0	1	
Pumping and Water Bleeding	0	4	0	1	5	
Reactive Aggregate Durability Distress	0	0	0	0		
Scaling, Map Cracking and Crazing	1	0	0	0	1	
Spalling (Transverse and Longitudinal Joints)	1	0	0	0	1	
Spalling (Corner)	0	0	0	0		
Swell	0	0	0	0		
Transverse and Diagonal Cracks	0	0	0	0		
	21	7	17	12		
JOINTED REINFORCED CONCRETE DISTRESS						
Blow-up	2	0	10	10	22	1
Corner Break	0	0	0	1	1	
Depression	2	3	2	0	7	5
Durability ("D") Cracking	0	0	0	0		
Faulting of Transverse Joints and Cracks	8	0	1	0	9	2
Joint Load Transfer System Associated Deterioration	0	0	0	0		
Joint Seal Damage of Transverse Joints	1	0	0	0	1	
Longitudinal Cracks	0	0	0	0		
Longitudinal Joint Faulting	2	0	1	0	3	
Patch Deterioration	3	0	3	1	7	5
Popouts	1	0	0	0	1	
Pumping and Water Bleeding	0	4	0	1	5	
Reactive Aggregate Durability Distress	0	0	0	0		
Scaling, Map Cracking and Crazing	1	0	0	0	1	
Spalling (Transverse and Longitudinal Joints)	1	0	0	0	1	
Spalling (Corner)	0	0	0	0		
Swell	0	0	0	0		
Transverse and Diagonal Cracks	0	0	0	0		
	21	7	17	13		
CONTINUOUSLY REINFORCED CONCRETE DISTRESS						
Asphalt Patch Deterioration	3	0	3	1	7	5
Blow-up	2	0	10	10	22	1
Concrete Patch Deterioration	2	0	2	1	5	
Construction Joint Distress	1	0	0	0	1	
Depression	2	3	2	0	7	
Durability ("D") Cracking	0	0	0	0		
Edge Punchout	0	0	0	1	1	
Localized Distress	0	0	0	1	1	
Longitudinal Cracking	0	0	0	0		
Longitudinal Joint Faulting	2	0	1	0	3	
Popouts	1	0	0	0	1	
Pumping and Water Bleeding	0	4	0	1	5	
Reactive Aggregate Distress	0	0	0	0	0	
Scaling, Map Cracking and Crazing	1	0	0	0	1	
Spalling	1	0	0	0	1	
Swell	0	0	0	0	0	
Transverse Cracking	0	0	0	0		
	15	7	18	15		

time and resources was directed toward developing a primary data base that could be used to determine these required relationships. This effort produced 240 sections being monitored in ten states. An analysis of the initial condition of these sections was used to validate predictions of pavement behavior. However, the sections must be monitored for a period of time, following various maintenance treatments, before a suitable data base exists that can be evaluated to create the required performance prediction equations.

The ability to predict the performance of maintainable elements following different maintenance treatments is critical to the credibility of the methodology, and so precludes making any assumptions that might discourage the implementation of study results. Maintenance practices differ from state-to-state and between jurisdictional units within states. One cannot simply specify the application of a surface treatment. The specifications for this activity vary widely because a range of asphaltic and aggregate materials are used. Also varied are the gradation of aggregates, the use of polymers or other additives, and the extent of surface preparation prior to surface treatment. In addition to these variations, one needs to address the range of pavement designs and conditions being treated and the different environments (climate, traffic, subgrades) where the pavement must perform.

The principal variables considered significant in predicting pavement performance include the pavement structure, material properties, traffic and load distribution, and the environment. These categories include 59 individual items in the Long-Term Pavement Performance study (LTPP) and are by pavement type. Another dozen items are monitored to gage pavement performance. If two levels were established for each of the 59 variables, the possible number of combinations would be $(2)^{59}$ or 5.76×10^{17}. Obviously, all variables cannot be included. The approach taken in LTPP was to design an experiment around the most significant factors. For asphaltic concrete pavements, this included 7 factors and a requirement for 384 test sections. The 7 factors control test site selection, but each of the 59 applicable variables is quantified.

To determine the effectiveness of a given maintenance treatment one must first address the factors affecting pavement performance. Then, the maintenance variables are added. These include (1) pavement condition at the time of treatment, (2) weather conditions at time of treatment, (3) amount of time that completed treatment is closed to traffic, and (4) traffic volume and composition. If just one treatment on asphaltic concrete pavements is examined and each maintenance variable is held to two levels, one will need $2^4 \times 384$ sections, i.e., 6,144 sections. There are easily a dozen treatment options worthy of investigation.

Given the large number of maintenance responses (treatments), the different ways in which each might take form, and the need to have a creditable methodology, the project staff determined that they could not, at this time, predict the performance of a maintained highway element following a specific maintenance treatment. Instead, a methodology was created that generates the consequences of performing any maintenance the effectiveness of which is a user-specified input. In this way, users would be able to provide a more realistic assessment of the effectiveness of a given treatment, particularly for their jurisdictional or geographical area, than the researchers could model at this time. The researchers used available though limited data to predict the performance of select pavements following specific treatments to illustrate the methodology. But, for the general user of the methodology, the effectiveness of any specific maintenance treatment should be a methodology input.

The resulting methodology is judged to have considerable value. The user is able to investigate a large number of treatments conceptually. For example, one can specify a treatment that prolongs a pavement service life 1, 2, or 3 years. The consequences of each treatment can be determined. This permits an agency to evaluate the warrants for different treatments. For example, if the inclusion of an additive results in 6 months added life and makes the treatment costs 10 percent more, the cost effectiveness of the additive can be determined. Another example of using the methodology is to determine the most effective treatment life and cost scenario and then develop or find a treatment to satisfy that scenario.

MICROPROCESSOR BASED

Microcomputer memory limitations require small programs dealing with a specific analysis rather than one large program. The advantages of small programs are that effects and sensitivities of specific variables can be better understood, and the programs can be implemented at the user's pace. With the large integrated programs designed for mainframes, the decision-maker may change a variable and never be quite sure how that variable interacts with others in the program. In addition, the costs to run large programs on a mainframe may limit sensitivity analyses. This is especially important if the user is only interested in one facet of the analysis. A disaggregated series of programs designed to be run on microcomputers allows users to obtain specific analysis results. The decision-maker can implement the programs at a comfortable pace, possibly by assigning a junior staff member to become familiar with one or more of the programs, and adding more programs as additional analyses become desired.

The following computer programs were developed to support the use of the methodology on microprocessors:

1. AGENCY—Determines agency maintenance, restitution, rehabilitation, resurfacing, and reconstruction costs for a given pavement maintenance strategy.
2. BLCCA—Determines agency maintenance, restitution, rehabilitation, resurfacing, and reconstruction costs for a given bridge maintenance strategy.
3. IMPACT—Calculates vehicle-operating costs during the analysis period, determines road-occupancy hours for traffic closures and maintenance strategies, and computes the consequences in terms of vehicle operating costs, accidents, pollution, user comfort, and time.

AGENCY METHODOLOGY

The steps required to make an economic analysis of agency costs for different pavement maintenance strategies, are as follows:

1. Characterize the pavement in terms of its type, age, structural strength, serviceability, surface area, and any existing distress.

2. Specify the expected 18-kip axle loading (EAL) and growth rate.
3. Define a discount rate for the opportunity cost of money and the terminal serviceability that will activate rehabilitation.
4. Identify the environment in terms of average annual precipitation, freezing index, maximum difference temperature, and Thornthwaite moisture index.
5. Provide the unit costs and productivity for each treatment used to maintain or rehabilitate the pavement and the effectiveness of the treatment in retarding and correcting the deterioration being addressed.
6. Repeat the treatments as needed, based on their effectiveness, throughout the analysis period and accumulate discounted treatment costs. The analysis period is defined by either the time taken to reach terminal serviceability, or 50 years if terminal serviceability is not reached.
7. Add to the maintenance costs the discounted costs to restore serviceability at the end of the analysis period.
8. Output annualized agency cost for the analysis period, the quantity of each treatment, its timing and average pavement serviceability annually.

The program consists of a series of damage models that predict the future condition of the pavement. The damage models predict distress, and a distribution is associated with each distress and is used in concert with maintenance service levels to determine maintenance activity workload.

The distress is treated as evolutionary, i.e., one form of distress not corrected leads to another distress of a more serious nature. As an example, rigid pavement pumping creates voids under the pavement which, if uncorrected, leads to faulting, edge and transverse cracking, and finally holes in the pavement. The activities available to stop or retard this process are built into the program. The users identify the specific treatments they would use for each activity and the effectiveness of each treatment. The effectiveness takes two forms. First, the treatment may extend the serviceability of the pavement which will delay rehabilitation. Second, the treatment may only correct a local condition or hazard and not influence the overall performance of the pavement. In this case, we want to know the permanence of the treatment. For example, a temporary patch may serve for only one year. It will be repeated each year until the pavement is rehabilitated.

All distress follows some distribution; for example, joint sealants do not fail at some singular time. The material in some joints fails prior to that of others, so failures follow a distribution. As another example, where rigid pavements are faulting, the severity of faulting increases with time. The average faults can be predicted, but the faults vary from some low value to some extreme value. Again, a distribution defines this distress and, for faulting, is illustrated in Figure 5.

Maintenance Condition Threshold

Maintenance service level guides take the form of threshold maintenance conditions that activate an agency response. As pointed out earlier, maintenance conditions follow a distribution. The faulting distribution is shown in Figure 5. The average fault shown is three-eighths of an inch. This is the faulting value predicted by the damage model. Average distress does not make a particularly good threshold because it is difficult to judge. Instead, more extreme conditions are specified. For example, a guide might be to correct faulting when individual faults exceed 1 in. This means that maintenance forces would be sent to correct faulting when the supervisor establishes that faults have reached a 1-in. severity. Actually, the 1 in. is not likely to be a good threshold because such a value occurs infrequently. A better threshold should fall somewhere in the 90 to 95 percentile range in the distribution. This would represent a level of distress easily recognized by the maintenance supervisor or foreman responsible for identifying maintenance needs. Therefore, the service level guide (threshold) needs to be a value that is readily observed in the field. A good example for the distribution in this study would be 5 percent or more of the faults exceeding 3/4 in. This is a reasonable guide with which to trigger a maintenance response.

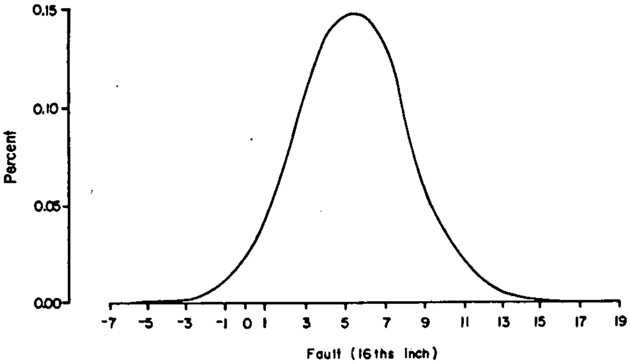


Figure 5. Typical faulting distribution in the driving lane.

Workload

If the problem or distress that is being addressed is rigid pavement faulting, one wants to eliminate the fault. One option is to just overlay; however, this does not correct the underlying causes and is not considered good practice. Therefore, a sequence of activities have been built into the program that represent accepted practice. This sequence is as follows:

1. Replace entirely any badly broken slabs.
2. Replace with full-depth concrete patches any disintegrated portions of a slab.
3. Replace spalled areas with partial depth portland cement patches.
4. Underseal voids.
5. Grind faults.
6. Reseal all joints and cracks.

A maintenance workload needs to be established for each of these activities. Models have been built into the program and distributions relating faulting, voids, joint deterioration, slab deterioration, and cracking. The models predict distress as a function of traffic, the environment, and the characteristics of the pavement, including slab length, the addition of lateral drains, load transfer dowel bars, and tied concrete shoulders.

The workload depends on the threshold specified and the extent of repairs. Therefore, for faulting, not only is the threshold identified but also the extent to which faults are corrected. Examining the faulting distribution in Figure 5, one sees that faults range from zero to 1 in. There is no need to correct zero faults, but one may want to correct the voids under the pavement that contribute to faulting. The program accommodates different levels of correction relative to extent. Therefore, one can correct all faults in excess of 1/4 in. or 0 in. or implement a preventive program and correct all faults plus a percentage of the voids that have not yet led to faulting.

The analysis is designed so that a maintenance strategy can be implemented at any point in the pavement's service life. Therefore, initial condition in terms of the extent of existing distress must be specified. Also, the extent and severity of maintenance are determined from the condition of the pavement and are based on an evaluation of actual records of agency response to pavements in different condition.

Maintenance Costs

Maintenance costs are based on the application of maintenance performance standards to the estimated quantity of maintenance work activity. The damage models predict average distress, but this must be converted to maintenance activity work accomplishment units. The specified maintenance service level determines the magnitude and extent of distress that will be corrected.

Included in the program AGENCY are representative performance standards for a range of maintenance activities. These are based on an examination of performance standards from 20 state agencies (*11*), and an evaluation of achievable productivity based on *NCHRP Report 161* (*12*). The activity unit costs used in testing the program "AGENCY" represent a consensus combination of labor, equipment and materials, average labor values (*13*) and typical equipment rentals and material unit costs. The production units were defined to meet methodology requirements.

Prediction Models

The damage models from state agency records included in the program "AGENCY" are drawn from the literature albeit modified to reflect limited data developed during the study. These models predict average levels of distress for given pavement types subject to specific environmental and traffic influences. They do not predict the performance or condition of a specific pavement. Rather, they predict the average performance or conditions for pavements having the same characteristics and subject to the same influences. Therefore, the conditions of a pavement representative of a group are being predicted. Furthermore, for that representative pavement, the models predict a condition average; in other words, if rigid pavement faulting is predicted to be 0.25 in., this is the average of all faulting present on the pavement. The actual faults may vary from zero to half an inch. This is an important consideration because maintenance service levels are defined in terms of threshold conditions. Therefore, in addition to damage models, the program "AGENCY" includes distributions for predicted distress.

Economic Treatment

The economic treatment was established only after a review of a number of optional considerations including the cycle length, opportunity costs of capital, inflation, salvage value, and initial investments. First, examined was the objective to evaluate the consequences of performing different maintenance strategies. Because maintenance only begins after the facility has been built, of interest are the agency costs occurring following construction, these being principally maintenance expenditures. Of course, if maintenance is delayed or not performed, the facility may deteriorate quite rapidly and this means the initial investment is used up rapidly. If one could value the facility over time and evaluate the salvage value of the maintenance element being addressed, a mechanism would be available to consider these costs. However, the procedure to isolate the initial costs of maintenance elements that generate a maintenance condition was not apparent. Another approach is to determine the costs required to restore the maintenance element to its initial condition. This option was more attractive because maintenance elements are rehabilitated and the costs of these activities can be determined. Therefore, the researchers elected to ignore the initial costs of the maintenance element and assess the loss in the investment as being those rehabilitation costs required to restore the maintenance element to some predefined condition. Since the costs of rehabilitating the element must be included in the analysis, the analysis period is the years until rehabilitation. These years define the life cycle being considered in the methodology.

The options existed to consider current dollars or constant dollars in the economic analysis. The use of current dollars requires an estimate of costs at the time of investment. These costs are based on estimating inflation rates for labor, equipment, or select materials and, with precise forecasts, thus provide a good assessment of agency costs. It also means that the analysis results can be biased if actual inflation rates are different. The use of constant dollars eliminates the need to speculate about the future in arriving at an assessment of costs and is also a simpler procedure. To minimize the complexity of the methodology, the constant dollar approach was selected for example runs.

Although, the program allows the use of current dollars and inflation rates, it is recommended that this feature not be used for two reasons. First, using inflation rates requires that someone estimate rates for each type of maintenance treatment. To justify using inflation rates, the user must be very sure that the cost of one type of maintenance will inflate at a markedly different rate than another. If, for example, a highway agency *knows* that inflation of the cost of overlays will be dramatically different from inflation for surface treatments, using inflation rates might be justified. This is a big assumption, and involves information not usually known with any real confidence. As a note, if a user feels justified in using this feature, the market rate of interest must be used. This is the interest rate charged in the money market for projects of this type.

The second reason for not using different inflation rates involves confidence in the quality of data. These programs are not intended to be used to plan project level maintenance activities. The data generally available and the precision of the models are not of sufficient quality to justify using these programs for these purposes. The programs were meant to be used only as a tool to explore the relative merits of different maintenance service levels. And to use different inflation rates for different maintenance treatments would result in an attempt to too precisely "fine tune" the process.

The opportunity costs of capital must be considered at any time investments over time are being evaluated. This discount rate should reflect the real costs of capital which has been estimated at about 4 percent for low-risk investments. This rate is a methodology input and so can be varied to test the sensitivity of the analysis to changes in the discount rate.

Both maintenance element age and the analysis period have a substantial impact on agency costs. Therefore, the length of the analysis period will alter the results.

Annual discounted agency costs that include construction, rehabilitation, and maintenance become smaller as the life-cycle period is increased. Long periods may appear more equitable, but the probability of errors in forecasting traffic, vehicle mix, unit costs, and condition all increase which creates credibility problems.

Another consideration is the implication of decisions on managers. In many states, top management changes at intervals. If the positive consequences of good decisions are not realized during the tenure of the managers making the decisions, there may be little incentive to implement strategies that take a long time to produce favorable results. This is a warrant for short analysis periods.

Rehabilitation, in the form of overlays, is normally designed to restore the structural capacity of the pavement (as it was originally constructed). A reasonable analysis period is one that starts with a newly constructed or rehabilitated pavement and terminates with rehabilitation. If rehabilitations are executed when pavement serviceability reaches a predetermined terminal value, different strategies will require different analysis periods.

Accumulated present value costs cannot be directly compared because they represent different life-cycle analysis periods. An economic procedure is needed that permits one to equitably compare these costs. The procedure developed for that purpose is titled "Equivalent Uniform Annual Cost Method" (EUAC) (Ref. *14*). First, each year's expenditure for maintenance or rehabilitation is converted to a present worth, next all present worth expenditures are totaled, and finally the total is multiplied by a capital recovery factor to convert the total in year zero to a uniform annual cost flow. The consequence of reducing maintenance service levels, on an annual basis, is defined as the difference between annualized costs computed for two different maintenance service levels. Alternatively, the consequence can be expressed as a ratio. If the annualized cost ratio between a high maintenance level and a low maintenance produces a ratio of 1.2, this means that it costs 20 percent more to adopt the more costly strategy.

A summary of the economic treatment used in the pavement methodology is as follows:

1. All maintenance costs and rehabilitation costs are converted annually to a present value using the following:

$$PV = \text{Costs}/(1+i)^n$$

PV = present value, i = discount rate, and n = year.

2. All present value costs are annualized using the following:

$$AC = PV \times i/[1-1/(1+i)^n]$$

Table 3. Analysis parameters for rigid pavement example runs.

TRAFFIC		
ADT total in both directions, 10% trucks	4000	
	8000	
	12000	
ENVIRONMENTAL	BAD	GOOD
Average Annual Precipitation, cm	84	40
Freezing Index	625	0
Thornthwaite Moisture Index	20	-20
CONSTRUCTION PARAMETERS		
JPCP, slab thickness, inches	8	
	9	
	10	
JRCP, slab thickness, inches	8	
	9	
	10	
Dowel diameter	.125	
Doweled Joints		
CBR	2	
Non-stabilized subbase		
Fine grained soil		
MAINTENANCE PARAMETERS		
LOW		
- no undersealing		
- no grinding		
- no joint and crack sealing		
- no permanent PCC patching		
- 1 SY/lane mile/year temporary bituminous patching		
MODERATE		
- underseal when 20% of slabs have voids larger than 5 cubic feet		
- no grinding		
- replace all joint and crack sealant every 4 years		
- 10 SY/lane mile/year permanent PCC patching		
- 1 SY/lane mile/year temporary bituminous patching		
HIGH		
- underseal when 20% of slabs have voids larger than 5 cubic feet.		
- grind when mean fault larger than 0.2 inch		
- repalce all joint and crack sealant every 4 years		
- 10 sy/lane mile/year permanent PCC patching		
- 1 sy/lane mile/year temporary bituminous patching		

AGENCY EXAMPLE RUNS

Pavement performance is a blend of distress predictions and preventive maintenance activities. The PCC pavement section, traffic, environment, and analysis parameters shown in Table 3 were used to illustrate the use of the rigid pavement version of AGENCY.

The units applicable to each distress are:

- Mean void—Cubic feet
- Mean fault—Inches
- Mean cracking—Linear feet
- Patching—Square yards

Damage model distresses are based on a nominal maintenance level. The program user specifies the maintenance treatments and thresholds to be evaluated. For the example run these were:

1. Clean and seal all failed joints at a 4-year interval.
2. Patch with full-depth PCC patches all failed areas up to 10 SY of pavement per lane-mile annually.
3. Underseal the pavement when the mean void per slab exceeds 2 cu ft.
4. Grind faults when 10 percent of faults exceed 0.20 in.
5. Do up to 1 sq yd of temporary bituminous patching on failed areas annually.

Table 4 gives the results of these maintenance policies in terms of the quantity of each maintenance treatment performed in the simulation for these inputs by year.

Table 5 shows the maintenance's effect on the distress conditions. For example, the grinding in year 18 improved PSI from 2.03 to 2.16 and reduced the mean fault. The undersealing in year 11 reduced the mean void in year 12. Residual patching is the square yards of pavement that require patching. This is the difference between predicted and that executed.

Table 6 shows the days the pavement is occupied to perform maintenance. These days are based on daily treatment productivities input to the program. The line, PREREHAB, represents the effort needed to correct all distress prior to a pavement overlay.

Finally, Table 7 shows the maintenance and rehabilitation costs associated with this run scenario. The costs shown are constant dollars in the year of treatment. They are based on treatment unit cost inputs to the program. The costs are also shown in terms of a present value based on the input discount rate and annualized at that discount rate. The total annualized cost for all maintenance, prerehabilitation, and resurfacing is $2,672.00 per year. This is one complete cycle covering the pavement performance from an initial PSI of 4.5 to a terminal PSI of 2.0.

A series of rigid pavement AGENCY runs were made for similar pavements for three maintenance levels shown in Table 3. The results for each combination of traffic and pavement thickness are illustrated in Figures 6 to 9. These figures show relative maintenance expenditures and pavement life for both reinforced and plain jointed concrete pavements in good and bad environments for a variety of terminal PSIs, traffic loadings, slab thicknesses, and maintenance service levels. Each block in the figure corresponds to a combination of these variables. The numbers in each block are the factored cost above the life in years. A bad environment for pavements was represented by conditions present in Illinois, while good conditions were represented by conditions in southern California. The factors are based on the ratio of all annualized costs to the minimum cost treatment which was low maintenance, 12-in. pavement, low traffic volume. For the inputs specified, the low maintenance level proved less costly in terms of agency costs for all combinations. The dollar value of a factor of 1 is shown below each figure.

Table 8 is a list of inputs for an example run of the flexible pavement version of AGENCY.

The program user specifies maintenance treatment and thresholds for the evaluation; for example:

1. Reseal with a surface treatment every 5 years.
2. Patch up to 0.5 sq yd per mile of the area with severe distress.

Table 9 shows the results of the policies in terms of quantities of each maintenance treatment each year, while Table 10 shows the effect of maintenance on distress. For example, in year 9, all cracking covered 41 percent of the pavement surface as did wide cracks (AASHTO class 4 cracking). The percent cracking for both types was reduced to zero for one year by a slurry seal.

Table 11 shows the days the pavement is occupied for performing maintenance based on productivity rates input by the program user.

Table 12 shows maintenance and rehabilitation costs for this

Table 4. Table of maintenance performed.

YEAR	J&C SEALING	UNDERSEALING	GRINDING	PERMANENT PATCHING	TEMPORARY PATCHING
1	.00	.00	.00	.00	.00
2	.00	.00	.00	.01	.00
3	.00	.00	.00	.02	.00
4	4224.00	.00	.00	.04	.00
5	.00	.00	.00	.09	.01
6	.00	.00	.00	.21	.02
7	.00	.00	.00	.45	.05
8	4224.00	.00	.00	.96	.11
9	.00	.00	.00	1.92	.21
10	.00	.00	.00	3.57	.40
11	.00	.00	.00	5.79	.64
12	4224.00	727.24	.00	8.05	.89
13	.00	.00	.00	9.73	1.08
14	.00	.00	.00	10.91	1.21
15	.00	.00	.00	11.69	1.30
16	4224.01	.00	.00	12.10	1.34
17	.00	.00	.00	12.28	1.36
18	.00	.00	1760.00	12.41	1.38
19	.00	.00	.00	12.54	1.39
20	4224.02	.00	.00	12.57	1.40
21	.00	.00	.00	12.54	1.39
22	.00	.00	.00	12.56	1.40
23	.00	.00	.00	12.63	1.40
24	4224.03	.00	.00	12.63	1.40
25	.00	.00	.00	12.58	1.40
26	.00	.00	.00	12.59	1.40
PREREHAB	422.44	616.32	1337.60	9.83	

Table 5. Table of distress conditions.

	PSI	MEAN VOID	MEAN FAULT	SEALS	RESIDUAL PERMANENT PATCHING	RESIDUAL TEMPORARY PATCHING
1	4.06	.49	.01	84.48	.00	.00
2	3.92	.71	.01	422.40	.00	.00
3	3.78	.89	.02	1098.24	.00	.00
4	3.64	1.05	.02	.00	.00	.00
5	3.50	1.19	.03	84.48	.00	.00
6	3.35	1.33	.04	422.40	.00	.00
7	3.21	1.46	.04	1098.24	.00	.00
8	3.07	1.59	.05	.00	.00	.00
9	2.93	1.71	.06	84.48	.00	.00
10	2.79	1.83	.06	422.40	.00	.00
11	2.64	1.95	.07	1098.24	.00	.00
12	2.50	.01	.08	.00	.00	.00
13	2.35	.13	.08	84.48	.00	.00
14	2.21	.24	.09	422.40	.00	.00
15	2.06	.36	.10	1098.25	.00	.00
16	2.04	.48	.11	.00	.00	.00
17	2.03	.60	.11	84.49	.00	.00
18	2.16	.73	.00	422.41	.00	.00
19	2.15	.85	.01	1098.25	.00	.00
20	2.13	.97	.02	.00	.00	.00
21	2.11	1.10	.03	84.50	.00	.00
22	2.08	1.22	.04	422.42	.00	.00
23	2.06	1.35	.05	1098.26	.00	.00
24	2.03	1.48	.06	.00	.00	.00
25	2.00	1.62	.07	84.51	.00	.00
26	1.97	1.75	.08	422.44	.00	.00

Table 6. Table of days of maintenance.

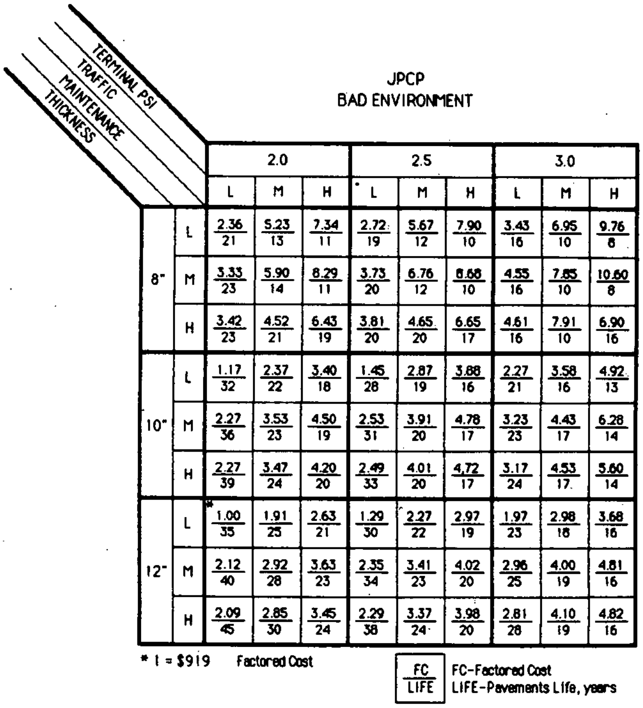
YEAR	J&C SEALING	UNDERSEALING	GRINDING	PERMANENT PATCHING	TEMPORARY PATCHING
1	.00	.00	.00	.00	.00
2	.00	.00	.00	.00	.00
3	.00	.00	.00	.00	.00
4	2.17	.00	.00	.00	.00
5	.00	.00	.00	.00	.00
6	.00	.00	.00	.01	.00
7	.00	.00	.00	.02	.00
8	2.17	.00	.00	.04	.00
9	.00	.00	.00	.09	.00
10	.00	.00	.00	.16	.00
11	.00	.00	.00	.26	.00
12	2.17	14.54	.00	.36	.01
13	.00	.00	.00	.43	.01
14	.00	.00	.00	.48	.01
15	.00	.00	.00	.52	.01
16	2.17	.00	.00	.54	.01
17	.00	.00	.00	.55	.01
18	.00	.00	11.28	.55	.01
19	.00	.00	.00	.56	.01
20	2.17	.00	.00	.56	.01
21	.00	.00	.00	.56	.01
22	.00	.00	.00	.56	.01
23	.00	.00	.00	.56	.01
24	2.17	.00	.00	.56	.01
25	.00	.00	.00	.56	.01
26	.00	.00	.00	.56	.01
PREREHAB	.22	12.33	8.57	.44	

DAYS FOR RESURFACING = 8.53

Table 7. Table of maintenance costs.

YEAR	J&C SEALING	UNDERSEALING	GRINDING	PERMANENT PATCHING	TEMPORARY PATCHING
1	.00	.00	.00	.20	.00
2	.00	.00	.00	.45	.01
3	.00	.00	.00	.99	.02
4	2956.80	.00	.00	2.22	.05
5	.00	.00	.00	4.89	.10
6	.00	.00	.00	10.83	.22
7	.00	.00	.00	23.59	.49
8	2956.80	.00	.00	50.10	1.04
9	.00	.00	.00	100.78	2.09
10	.00	.00	.00	187.29	3.88
11	.00	.00	.00	303.26	6.29
12	2956.80	1425.40	.00	421.65	8.74
13	.00	.00	.00	510.09	10.58
14	.00	.00	.00	571.79	11.86
15	.00	.00	.00	612.55	12.70
16	2956.80	.00	.00	634.10	13.15
17	.00	.00	.00	643.38	13.34
18	.00	.00	3520.00	650.39	13.49
19	.00	.00	.00	657.06	13.63
20	2956.81	.00	.00	658.92	13.66
21	.00	.00	.00	657.27	13.63
22	.00	.00	.00	658.39	13.65
23	.00	.00	.00	661.88	13.73
24	2956.82	.00	.00	661.94	13.73
25	.00	.00	.00	659.21	13.67
26	.00	.00	.00	659.64	13.68
PREREHAB	295.71	1207.98	2675.20	515.30	
PRESENT VALUE	11152.02	1379.05	2810.59	5274.29	105.37
ANNUAL	713.86	88.28	179.91	337.62	6.74

ANNUALIZED COST OF REHABILITATION WORK NOT INCLUDING
SEALING, UNDERSEALING, GRINDING, AND PATCHING 1352.36
TOTAL ANNUALIZED COST = 2672.02



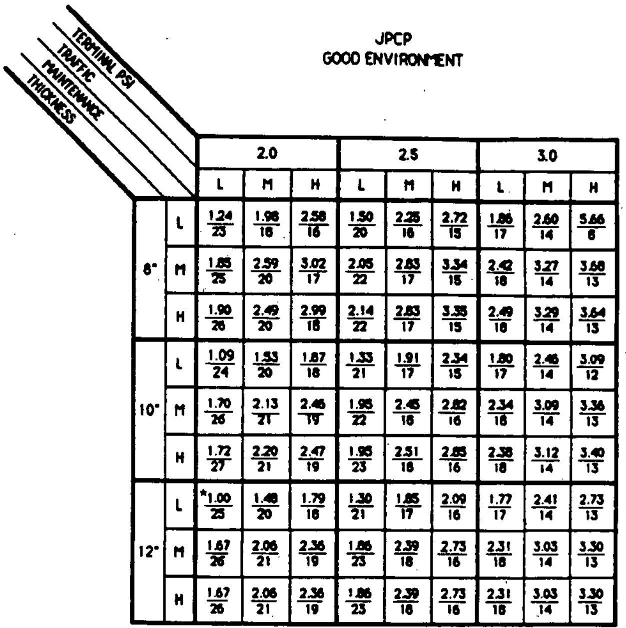
JPCP
BAD ENVIRONMENT

TERMINAL PSI		2.0			2.5			3.0		
TRAFFIC		L	M	H	L	M	H	L	M	H
THICKNESS	MAINTENANCE									
8"	L	2.36 21	5.23 13	7.34 11	2.72 19	5.67 12	7.90 10	3.43 16	6.95 10	9.76 8
	M	3.33 23	5.90 14	8.29 11	3.73 20	6.76 12	8.68 10	4.55 16	7.85 10	10.60 8
	H	3.42 23	4.52 21	6.43 19	3.81 20	4.65 20	6.65 17	4.61 16	7.91 10	6.90 16
10"	L	1.17 32	2.37 22	3.40 18	1.45 28	2.87 19	3.88 16	2.27 21	3.58 16	4.92 13
	M	2.27 36	3.53 23	4.50 19	2.53 31	3.91 20	4.78 17	3.23 23	4.43 17	6.28 14
	H	2.27 39	3.47 24	4.20 20	2.49 33	4.01 20	4,72 17	3.17 24	4.53 17	5.60 14
12"	L	*1.00 35	1.91 25	2.63 21	1.29 30	2.27 22	2.97 19	1.97 23	2.98 18	3.68 16
	M	2.12 40	2.92 28	3.63 23	2.35 34	3.41 23	4.02 20	2.96 25	4.00 19	4.81 16
	H	2.09 45	2.85 30	3.45 24	2.29 38	3.37 24	3.98 20	2.81 28	4.10 19	4.82 16

* 1 = $919 Factored Cost

FC / LIFE: FC-Factored Cost
LIFE-Pavements Life, years

Figure 6. Relative maintenance expenditures JPCP—bad environment.



JPCP
GOOD ENVIRONMENT

TERMINAL PSI		2.0			2.5			3.0		
TRAFFIC		L	M	H	L	M	H	L	M	H
THICKNESS	MAINTENANCE									
8"	L	1.24 23	1.98 18	2.58 16	1.50 20	2.28 18	2.72 15	1.86 17	2.60 14	5.66 8
	M	1.85 25	2.59 20	3.02 17	2.05 22	2.83 17	3.34 15	2.42 18	3.27 14	3.68 13
	H	1.90 26	2.49 20	2.99 18	2.14 22	2.83 17	3.35 15	2.49 18	3.29 14	3.64 13
10"	L	1.09 24	1.53 20	1.87 18	1.33 21	1.91 17	2.34 15	1.80 17	2.46 14	3.09 12
	M	1.70 26	2.13 21	2.46 19	1.95 22	2.45 18	2.82 16	2.34 18	3.09 14	3.36 13
	H	1.72 27	2.20 21	2.47 19	1.95 23	2.51 18	2.85 16	2.38 18	3.12 14	3.40 13
12"	L	*1.00 25	1.48 20	1.79 18	1.30 21	1.85 17	2.09 16	1.77 17	2.41 14	2.73 13
	M	1.67 26	2.06 21	2.36 19	1.86 23	2.39 18	2.73 16	2.31 18	3.03 14	3.30 13
	H	1.67 26	2.06 21	2.36 19	1.86 23	2.39 18	2.73 16	2.31 18	3.03 14	3.30 13

* 1 = $1584

FC / LIFE: FC-Factored Cost
LIFE-Pavements Life, years

Figure 7. Relative maintenance expenditures JPCP—good environment.

JRCP
BAD ENVIRONMENT

THICKNESS	TERMINAL PSI / TRAFFIC / MAINTENANCE	2.0			2.5			3.0		
		L	M	H	L	M	H	L	M	H
8"	L	2.06 24	4.21 17	7.84 13	2.34 22	4.19 15	7.76 12	2.88 19	4.97 14	7.81 11
	M	2.64 27	5.00 18	8.18 14	2.94 24	5.11 17	8.19 13	3.52 20	5.81 14	8.47 12
	H	2.55 29	4.84 20	8.27 14	2.90 25	5.21 17	8.28 13	3.41 21	5.69 15	8.58 12
10"	L	1.25 32	2.08 25	3.28 20	1.47 29	2.33 23	3.45 19	1.87 25	2.80 20	3.86 17
	M	1.90 37	2.74 28	3.92 23	2.10 33	2.91 26	4.10 21	2.36 29	3.25 23	4.44 19
	H	1.76 44	2.59 33	3.95 26	1.92 39	2.82 29	4.11 24	2.18 33	3.13 25	4.35 21
12"	L	*1.00 36	1.30 32	1.71 28	1.16 33	1.52 29	1.90 26	1.45 29	1.80 26	2.26 23
	M	1.63 44	1.92 38	2.29 33	1.80 39	2.11 34	2.49 30	1.97 35	2.35 30	2.73 27
	H	1.58 50	1.77 47	2.13 41	1.59 49	1.89 42	2.26 37	1.59 40	2.11 36	2.50 32

* 1 = $806

FC LIFE	FC-Factored Cost LIFE-Pavements Life, years

Figure 8. Relative maintenance expenditures JRCP—bad environment.

JRCP
GOOD ENVIRONMENT

THICKNESS	TERMINAL PSI / TRAFFIC / MAINTENANCE	2.0			2.5			3.0		
		L	M	H	L	M	H	L	M	H
8"	L	1.33 28	2.547 19	3.362 16	1.703 24	2.967 17	3.997 14	2.241 20	3.851 14	4.873 12
	M	1.887 31	3.049 20	3.987 16	2.160 27	3.399 18	4.589 14	2.767 21	4.166 15	5.430 12
	H	1.596 37	2.617 23	2.616 24	1.883 31	3.005 20	3.925 16	2.543 23	3.820 16	4.884 13
10"	L	1.005 33	2.284 22	1.565 27	1.249 29	1.576 26	1.861 24	1.803 23	2.164 21	2.588 19
	M	1.527 39	1.779 34	2.063 30	1.755 33	2.053 29	2.365 26	2.221 26	2.613 23	2.914 21
	H	1.287 50	1.407 46	1.674 39	1.378 45	1.590 39	1.853 34	1.839 32	2.030 29	2.424 25
12"	L	*1.000 33	1.198 31	1.351 30	1.245 30	1.484 27	1.666 26	1.793 23	2.012 22	2.251 21
	M	1.489 40	1.654 37	1.861 34	1.712 34	1.886 32	2.134 29	2.215 26	2.484 24	2.692 23
	H	1.305 50	1.340 50	1.514 46	1.424 44	1.451 44	1.652 40	1.859 32	1.805 33	2.057 30

*1 = $955

FC LIFE	FC-Factored Cost LIFE-Pavements Life, years

Figure 9. Relative maintenance expenditures JRCP—good environment.

Table 8. Flexible pavement example run analysis parameters.

Traffic	
ADT total in both direction 33% trucks	1700
Construction parameters	
Pavement type	Asphalt concrete on granular base
Structural number	3.64
Maintenance parameters	Reseal every 5 years
	Patch 0.5 square yards/mile

scenario. Costs are based on unit costs input to the program and are present valued and annualized using a discount rate of 5 percent.

Table 13 lists inputs for a series of runs made for flexible pavements. The results are shown in Figure 10, with factors based on a ratio of total annualized costs to the lowest cost option. The dollar amount of a factor of 1 is shown below the figure. As with the figures for rigid pavements, each block contains the factored cost and pavement life in years.

BLCCA METHODOLOGY

The life-cycle agency costs for different bridge maintenance strategies considers a life-cycle period that ends with the bridge being replaced. The methodology can be used for any bridge type from low cost, short-lived timber bridges to long-lived, reinforced concrete structures. The evaluation process requires that a user identify the bridge construction costs, the expected bridge life as a function of any maintenance treatments, and the costs of the maintenance treatments. The inputs are based on the user analyzing their structure inventory and appraisal (SI&A) files that are prepared at least biennially and submitted to the Federal Highway Administration for incorporation into the National Bridge Inventory. Also needed by the states are bridge maintenance expenditures by bridge related to activities that impact structure condition. The procedure for analyzing this information is given in Figure 11. A detailed example of the process is included in Appendix C for one maintenance activity using the North Carolina Department of Transportation data base.

The major limitation to the methodology is the limited history of data available, which required the application of 4.5 years of data in a cross sectional analysis to evaluate the effect of maintenance treatments on a 50-year bridge-life cost cycle. The major value of the methodology developed is in evaluating alternative maintenance service levels on life-cycle costs. This is done using the microcomputer program "BLCCA" (Bridge Life Cycle Cost Analyzer) which automates the economic evaluation of different maintenance scenarios. The road user or nonuser is impacted by bridge maintenance when a lane or bridge closure is required. This occurs when the bridge deck requires repairs or replacement, may occur during painting, and can be occasioned by the need to replace a bridge structural element. With the exception of bridge deck roughness on vehicle operating costs on long structures, the major impact is traffic interference due to lane closures.

IMPACT METHODOLOGY

Maintenance strategies influence road users in two ways. First, road surface conditions affect vehicle operating costs, accidents, and user comfort. Second, the occupancy of a pave-

Table 9. Table of maintenance performed.

YEAR	PREVENTIVE	PATCHING	SEALING	OVERLAY	RECONSTRUCTION
1	.00	.50	.00	.00	.00
2	.00	.50	.00	.00	.00
3	.00	.50	.00	.00	.00
4	.00	.50	.00	.00	.00
5	.00	.00	7040.00	.00	.00
6	.00	.00	.00	.00	.00
7	.00	.50	.00	.00	.00
8	.00	.50	.00	.00	.00
9	.00	.50	.00	.00	.00
10	.00	.00	7040.00	.00	.00
11	.00	.50	.00	.00	.00
12	.00	.50	.00	.00	.00
13	.00	.50	.00	.00	.00
14	.00	.50	.00	.00	.00
15	.00	.00	7040.00	.00	.00
16	.00	.50	.00	.00	.00
17	.00	.50	.00	.00	.00
18	.00	.50	.00	.00	.00
19	.00	.50	.00	.00	.00
20	.00	.00	7040.00	.00	.00
21	.00	.50	.00	.00	.00
22	.00	.50	.00	.00	.00
23	.00	.50	.00	.00	.00
24	.00	.50	.00	.00	.00
25	.00	.00	7040.00	.00	.00
26	.00	.50	.00	.00	.00
27	.00	.50	.00	.00	.00
28	.00	.50	.00	.00	.00
29	.00	.50	.00	.00	.00
30	.00	.00	7040.00	.00	.00
31	.00	.50	.00	.00	.00
32	.00	.50	.00	.00	.00
33	.00	.50	.00	.00	.00
34	.00	.50	.00	.00	.00
35	.00	.00	7040.00	.00	.00
36	.00	.50	.00	.00	.00
37	.00	.50	.00	.00	.00
38	.00	.50	.00	.00	.00
PREREHAB		99.99			

Table 10. Table of distress conditions.

YEAR	PSI	TOTAL CRACKING	WIDE CRACKING	RAVELING	POTHOLES	MEAN RUT	STANDARD DEVIATION
1	4.13	.52	.52	.00	.00	.09	.09
2	4.06	.59	.59	.00	.00	.11	.10
3	3.99	.66	.66	.00	.00	.12	.11
4	3.91	.75	.75	.00	.00	.13	.12
5	3.95	.00	.00	.00	.00	.14	.12
6	3.86	.00	.00	.00	.08	.15	.13
7	3.74	.67	.67	.00	.22	.16	.13
8	3.61	40.55	40.55	.00	.43	.16	.14
9	3.48	41.39	41.39	.00	.78	.17	.14
10	3.67	.00	.00	.00	.00	.18	.14
11	3.55	34.90	34.90	.00	.09	.18	.15
12	3.42	74.74	74.74	.00	.28	.19	.15
13	3.29	75.40	75.40	.00	.62	.19	.15
14	3.16	76.05	76.05	.00	1.10	.20	.16
15	3.40	.00	.00	.00	.00	.20	.16
16	3.28	34.91	34.91	.00	.09	.21	.16
17	3.15	74.75	74.75	.00	.28	.21	.16
18	3.01	99.39	99.39	.00	.61	.22	.17
19	2.88	98.86	98.86	.00	1.13	.22	.17
20	3.12	.00	.00	.00	.00	.23	.17
21	3.00	34.91	34.91	.00	.08	.23	.17
22	2.87	74.76	74.76	.00	.27	.23	.18
23	2.74	99.39	99.39	.00	.60	.24	.18
24	2.61	98.85	98.85	.00	1.14	.24	.18
25	2.82	.00	.00	.00	.00	.25	.18
26	2.71	34.91	34.91	.00	.08	.25	.18
27	2.59	74.76	74.76	.00	.27	.25	.18
28	2.46	99.39	99.39	.00	.60	.26	.19
29	2.34	98.83	98.83	.00	1.16	.26	.19
30	2.52	.00	.00	.00	.00	.26	.19
31	2.41	34.91	34.91	.00	.08	.27	.19
32	2.30	74.77	74.77	.00	.26	.27	.19
33	2.18	99.39	99.39	.00	.61	.27	.19
34	2.06	98.80	98.80	.00	1.19	.27	.20
35	2.22	.00	.00	.00	.00	.28	.20
36	2.12	34.92	34.92	.00	.08	.28	.20
37	2.01	74.77	74.77	.00	.26	.28	.20
38	1.90	99.38	99.38	.00	.61	.29	.20

ment or bridge deck to maintain or rehabilitate it interferes with traffic operations creating increased vehicle operating costs, higher risks of accidents, delays, and motorist inconvenience. The occupancy of a road also affects the non-road user since interfering with normal traffic flow creates stop and go traffic operations that raise the level of vehicle-contributed air pollution.

The consequences addressed by program IMPACT include:

1. Vehicle operation costs (fuel, oil, tires, maintenance and repair, and depreciation).
2. Lost time.
3. Accidents.
4. Pollution.
5. User comfort.
6. Interference time.

Program IMPACT computes the adverse effects (consequences) to road users and non-users for any maintenance strategy. The program is divided into two routines, one that addresses the influence of road surface conditions on user consequences and the second that evaluates traffic interference consequences. Both consequences are computed for the life-cycle analysis period.

Surface Condition Routine

The road surface condition considered is pavement or bridge deck roughness as expressed in present serviceability index (PSI) units. Computed are the effects of roughness on accidents, comfort, loss time, and vehicle operating costs. The consequences are presented as those in excess of road operations at some ideal level. The objective was to maximize analysis results sensitivity to different maintenance strategy specifications. Consequences not affected by maintenance strategy decisions were not included.

The differential consequences for surface roughness are based on the difference in consequences for operation on the road surface annually compared with a PSI value of 4.5 over the analysis cycle.

Table 11. Table of days of maintenance.

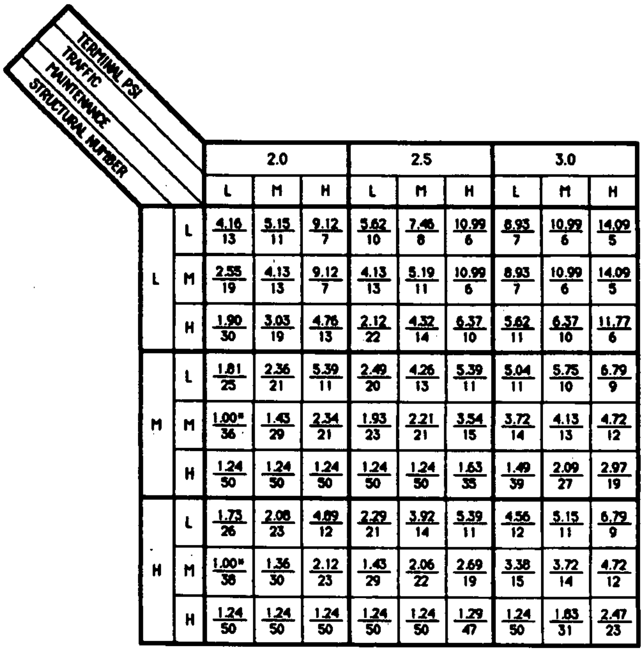
YEAR	PREVENTIVE	PATCHING	SEALING	OVERLAY	RECONSTRUCTION
1	.00	.03	.00	.00	.00
2	.00	.03	.00	.00	.00
3	.00	.03	.00	.00	.00
4	.00	.03	.00	.00	.00
5	.00	.00	1.76	.00	.00
6	.00	.00	.00	.00	.00
7	.00	.03	.00	.00	.00
8	.00	.03	.00	.00	.00
9	.00	.03	.00	.00	.00
10	.00	.00	1.76	.00	.00
11	.00	.03	.00	.00	.00
12	.00	.03	.00	.00	.00
13	.00	.03	.00	.00	.00
14	.00	.03	.00	.00	.00
15	.00	.00	1.76	.00	.00
16	.00	.03	.00	.00	.00
17	.00	.03	.00	.00	.00
18	.00	.03	.00	.00	.00
19	.00	.03	.00	.00	.00
20	.00	.00	1.76	.00	.00
21	.00	.03	.00	.00	.00
22	.00	.03	.00	.00	.00
23	.00	.03	.00	.00	.00
24	.00	.03	.00	.00	.00
25	.00	.00	1.76	.00	.00
26	.00	.03	.00	.00	.00
27	.00	.03	.00	.00	.00
28	.00	.03	.00	.00	.00
29	.00	.03	.00	.00	.00
30	.00	.00	1.76	.00	.00
31	.00	.03	.00	.00	.00
32	.00	.03	.00	.00	.00
33	.00	.03	.00	.00	.00
34	.00	.03	.00	.00	.00
35	.00	.00	1.76	.00	.00
36	.00	.03	.00	.00	.00
37	.00	.03	.00	.00	.00
38	.00	.03	.00	.00	.00
PREREHAB		6.67			

DAYS FOR RESURFACING = 6.40

Traffic Interference Routine

When a road is occupied to perform maintenance or rehabilitation, a portion is closed to traffic. On two-lane roads, this results in stopping traffic first in one direction and then in the opposite direction. This interference with traffic creates vehicle speed change cycles and idling that increases vehicle operating costs. The presence of the closure increases accident risk, delays traffic, and imposes an inconvenience on the road user.

The differential consequences for traffic interference is the increase in consequences created by road occupancy to perform maintenance.



		2.0			2.5			3.0		
		L	M	H	L	M	H	L	M	H
L	L	$\frac{4.16}{13}$	$\frac{5.15}{11}$	$\frac{9.12}{7}$	$\frac{5.62}{10}$	$\frac{7.46}{8}$	$\frac{10.99}{6}$	$\frac{8.93}{7}$	$\frac{10.99}{6}$	$\frac{14.09}{5}$
	M	$\frac{2.55}{19}$	$\frac{4.13}{13}$	$\frac{9.12}{7}$	$\frac{4.13}{13}$	$\frac{5.19}{11}$	$\frac{10.99}{6}$	$\frac{8.93}{7}$	$\frac{10.99}{6}$	$\frac{14.09}{5}$
	H	$\frac{1.90}{30}$	$\frac{3.03}{19}$	$\frac{4.76}{13}$	$\frac{2.12}{22}$	$\frac{4.32}{14}$	$\frac{6.37}{10}$	$\frac{5.62}{11}$	$\frac{6.37}{10}$	$\frac{11.77}{6}$
M	L	$\frac{1.81}{25}$	$\frac{2.36}{21}$	$\frac{5.39}{11}$	$\frac{2.49}{20}$	$\frac{4.26}{13}$	$\frac{5.39}{11}$	$\frac{5.04}{11}$	$\frac{5.75}{10}$	$\frac{6.79}{9}$
	M	$\frac{1.00^{*}}{36}$	$\frac{1.43}{29}$	$\frac{2.34}{21}$	$\frac{1.93}{23}$	$\frac{2.21}{21}$	$\frac{3.54}{15}$	$\frac{3.72}{14}$	$\frac{4.13}{13}$	$\frac{4.72}{12}$
	H	$\frac{1.24}{50}$	$\frac{1.24}{50}$	$\frac{1.24}{50}$	$\frac{1.24}{50}$	$\frac{1.24}{50}$	$\frac{1.63}{35}$	$\frac{1.49}{39}$	$\frac{2.09}{27}$	$\frac{2.97}{19}$
H	L	$\frac{1.73}{26}$	$\frac{2.08}{23}$	$\frac{4.89}{12}$	$\frac{2.29}{21}$	$\frac{3.92}{14}$	$\frac{5.39}{11}$	$\frac{4.56}{12}$	$\frac{5.15}{11}$	$\frac{6.79}{9}$
	M	$\frac{1.00^{*}}{38}$	$\frac{1.36}{30}$	$\frac{2.12}{23}$	$\frac{1.43}{29}$	$\frac{2.06}{22}$	$\frac{2.69}{19}$	$\frac{3.38}{15}$	$\frac{3.72}{14}$	$\frac{4.72}{12}$
	H	$\frac{1.24}{50}$	$\frac{1.24}{50}$	$\frac{1.24}{50}$	$\frac{1.24}{50}$	$\frac{1.24}{50}$	$\frac{1.29}{47}$	$\frac{1.24}{50}$	$\frac{1.83}{31}$	$\frac{2.47}{23}$

$\frac{\text{FACTORED COST}}{\text{LIFE (YEARS)}}$

* INDEXED VALUE = $847

Figure 10. Flexible sensitivity analysis.

Table 12. Table of maintenance costs.

```
YEAR       PREVENTIVE        PATCHING        SEALING         OVERLAY      RECONSTRUCTION
==========================================================================================
 1           .00              13.84            .00             .00             .00
 2           .00              13.84            .00             .00             .00
 3           .00              13.84            .00             .00             .00
 4           .00              13.84            .00             .00             .00
 5           .00                .00         3027.20            .00             .00
 6           .00                .00            .00             .00             .00
 7           .00              13.84            .00             .00             .00
 8           .00              13.84            .00             .00             .00
 9           .00              13.84            .00             .00             .00
10           .00                .00         3027.20            .00             .00
11           .00              13.84            .00             .00             .00
12           .00              13.84            .00             .00             .00
13           .00              13.84            .00             .00             .00
14           .00              13.84            .00             .00             .00
15           .00                .00         3027.20            .00             .00
16           .00              13.84            .00             .00             .00
17           .00              13.84            .00             .00             .00
18           .00              13.84            .00             .00             .00
19           .00              13.84            .00             .00             .00
20           .00                .00         3027.20            .00             .00
21           .00              13.84            .00             .00             .00
22           .00              13.84            .00             .00             .00
23           .00              13.84            .00             .00             .00
24           .00              13.84            .00             .00             .00
25           .00                .00         3027.20            .00             .00
26           .00              13.84            .00             .00             .00
27           .00              13.84            .00             .00             .00
28           .00              13.84            .00             .00             .00
29           .00              13.84            .00             .00             .00
30           .00                .00         3027.20            .00             .00
31           .00              13.84            .00             .00             .00
32           .00              13.84            .00             .00             .00
33           .00              13.84            .00             .00             .00
34           .00              13.84            .00             .00             .00
35           .00                .00         3027.20            .00             .00
36           .00              13.84            .00             .00             .00
37           .00              13.84            .00             .00             .00
38           .00              13.84            .00             .00             .00
==========================================================================================
PREREHAB                     2766.80
==========================================================================================
PRESENT      .00             191.15          9419.09           .00             .00
VALUE


ANNUAL       .00              11.44           563.64           .00             .00
ANNUALIZED COST OF PATCHING PRIOR TO RESURFACING      467.59
TOTAL ANNUALIZED COST =         1042.66
```

Table 13. Input factorial for flexible pavement runs.

Traffic	H	150,000	18 Kip (80kN) equivalent single axles/year
	M	50,000	18 Kip (80kN) ESAL
	L	10,000	18 Kip (80kN) ESAL
Structural Number	H	3.20	
	M	3.02	
	L	1.81	
Maintenance	H	reseal every 4 years	
	M	reseal every 8 years	
	L	reseal every 15 years	
Terminal PSI	H	3.0	
	M	2.8	
	L	2.0	

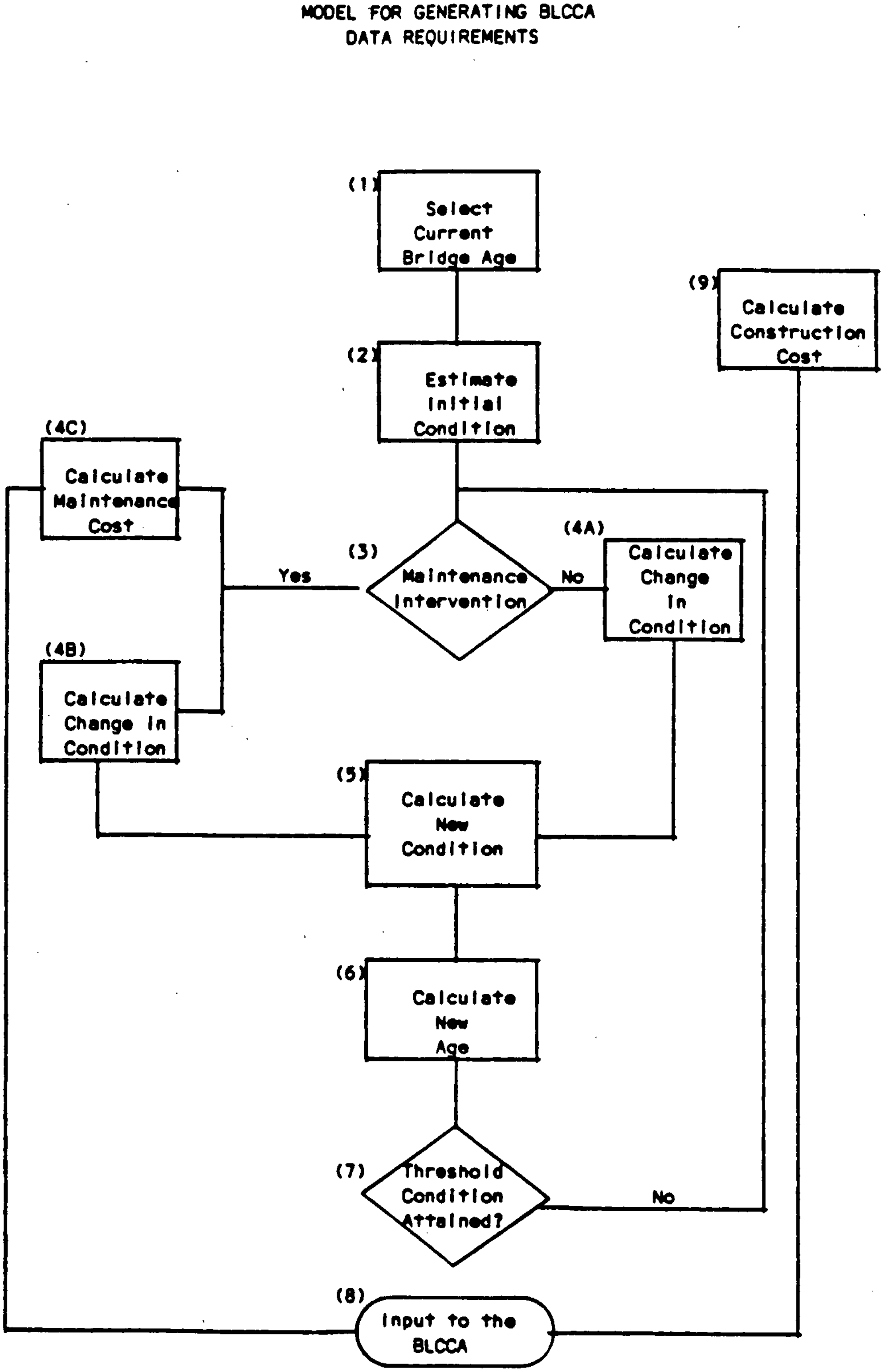


Figure 11. BLCCA flow chart.

CHAPTER THREE

INTERPRETATION, APPRAISAL, APPLICATION

The pavement methodology addresses the consequences of delaying the extent and timing of preventive pavement maintenance activities. These consequences include the accelerated deterioration of the pavement, poorer overall surface conditions, and earlier and more expensive rehabilitation. Poor highway conditions increase vehicle operating costs and increase the magnitude of corrective maintenance, which creates traffic interference. The consequences are increased vehicle operating costs, delays, pollution, higher accident risk, and added inconvenience to the road user.

The bridge methodology requires substantial user-supplied inputs. The program "BLCCA" is essentially an economic analysis of agency maintenance options. The impact on the bridge user can be evaluated using the program "IMPACT." This program compiles vehicle operating costs based on surface roughness and road closures, delays, pollution, accidents, and inconvenience. These are traffic interference outputs and can be determined for a bridge closure in the same manner as for a pavement closure.

INTERPRETATION AND APPRAISAL

The equations used in the program "AGENCY" do not predict the behavior of a particular pavement, only the aggregate behavior of pavements fitting a given category defined by traffic, climate, and its structural characteristics. The program handles pavement segments having specific characteristics, but these are generic pavements. They are not intended to be an actual pavement, but are typical of some portion of the network. The damage models predict the average condition of all pavements fitting into a typical segment category. The methodology evaluates the consequences of setting different maintenance levels for a segment having an arbitrary length. Likewise, the bridge methodology "BLCCA" is intended to compare alternative maintenance strategies for groups of bridges differentiated by structure type and, where possible, structure size.

The "AGENCY" methodology generates costs. Required as inputs are unit cost for the maintenance organization's activities. The tables in Chapter Two are presented as guides to be used by organizations who do not elect to execute the program AGENCY. The relative consequences of setting different maintenance service levels are presented as ratios of consequences for any proposed level to some reference level. Obtaining the absolute consequences for pavements requires multiplying the analysis consequences by the ratio of network mileage in the segment category by the segment length. An entire network can be evaluated by establishing road categories and defining a typical segment for each category. The consequences for bridges means multiplying the results for a bridge typical of the group by the number of bridges in the group.

The terms "project level" and "network level" planning is used in pavement management systems. These terms have been defined by Hudson et al. (*15*). The network or program management level is concerned with administrative decisions affecting road network programs, and project level decisions address more detailed technical decisions dealing with specific projects. The methodology developed in this study is a tool that can be used to guide decisions relative to network planning, not project planning. The level of sophistication of the models in this program, and the precision and quantity of data available to the user do not warrant using this program to establish maintenance schedules for specific pavements. The program was meant to be used as a tool to make relative assessments of costs and effectiveness of one maintenance level of service versus another on classes of pavements.

Accuracy

The trial use of "BLCCA" using the NCDOT bridge data identified a number of problems with the data's reliability that need to be highlighted. Subjective data when obtained over time by different groups or individuals will not be consistent and, although useful in assessing current conditions, have limited value in analyzing the relationships between maintenance treatments and performance. These relationships can only be determined using objective and accurate measures of condition that are repeatable over time. Furthermore, when the condition of a particular maintenance element is monitored, accurate records are needed of the timing and extent of specific maintenance treatments.

Limitations

Highway maintenance is not well defined and frequently depends on who does the work or who funds the work. These distinctions are not important to the methodology developed in this study because the types of maintenance activities that are to be included are defined.

Conditions that create a hazard to road users are given top priority by all maintenance organizations. These conditions include pavement or bridge deck obstructions or holes and extreme pavement dropoffs.

Delays in correcting such hazards are attributed to lack of notice or to an excessive number of such defects caused by abnormally severe weather. Maintenance organizations systematically correct all such defects as a top priority task since the consequences of not correcting such hazards are possible road user accidents. The literature search identified little quantitative information on the actual risk for specific defects. However, the objective guides that were found suggest that the defect must be quite extreme to actually create an accident. For example, shoulder dropoffs need to exceed 4 in. before they are considered unsafe, or potholes need to be 90 in. long and 6 in. deep before they cause a tire blowout (*16*). These are extreme conditions and current maintenance service level guides used by maintenance agencies require corrective action before such conditions evolve.

High maintenance service levels to correct potential hazards are warranted because road users, frequently through their own ineptness, do have accidents. Also, motorists may maneuver to avoid defects in the pavement surface and lose control of their vehicle. When an accident occurs, and if there is a defect in the road that can be identified as being the proximate cause of the accident, the maintenance organization often faces a tort suit. For these reasons, maintenance organizations give high priority to correcting potentially hazardous conditions.

Accidents or tort claim damages due to hazardous conditions are not predictable. Inasmuch as agencies have high service levels for hazardous conditions, there seems little point in guessing the consequences of not doing something that everyone does. Therefore, delays in correcting hazardous conditions are not addressed in the methodology.

Highway maintenance activities also address defects or hazardous conditions that are unavoidable regardless of maintenance service levels. These activities correct deficiencies created by poor construction, localized areas where below-standard materials have caused premature failures, and isolated locations where external factors beyond the control of the highway agency have created problems. This latter category includes such things as vandalism, spills, collisions, and floods. Maintenance workload generated by such events shows up in maintenance expenditure records, but does not reflect planned work directed towards preserving the maintenance element. It is not included in the evaluation methodology.

Some hazardous conditions are a direct result of delaying or not performing various preventive maintenance and so the evaluation of these conditions is included in the analysis of maintenance service levels. Agency policies may specify rehabilitation for terminal conditions that are extremely low. Such situations create maintenance workloads until the rehabilitation occurs. This work is included in the evaluation of service levels because rehabilitation timing has a major impact on both agency costs and user impacts. Also included are activities classified as resurfacing, restitution, or rehabilitation when major work does not restore the maintenance element to some predefined service level, e.g., a pavement serviceability of 3.5.

A difficult aspect of the bridge methodology pertains to the statistical analysis which must be performed to generate the BLCCA inputs. One must empirically discern the effect of different maintenance treatment combinations on bridge life expectancy because agencies combine different maintenance treatments into a single activity account. As these combinations become more complex in terms of treatments, timing, and the amount of maintenance, the actual number of bridges receiving a combination are reduced, leaving very small samples to statistically analyze.

In the test application, the maintenance activity performed on the structures examined was painting; yet, over a 4-year period only 125 or 5 percent of the 2,686 NCDOT structures were painted. This number does not constitute a large enough sample of painted bridges to differentiate by structure size, let alone by the amount of painting done. Nor was the sample large enough to explore combinations of maintenance activities such as painting and maintenance of timber structures.

Clearly, it is unlikely the data from any state would provide a sample of structures large enough to statistically analyze alternative maintenance approaches consisting of full arrays of activities performed over a 50 to 60-year life span. This suggests that the evaluation methodology is best suited for analyzing the cost effectiveness of single maintenance activities. To the extent that sufficient information for using BLCCA cannot be derived statistically, it is recommended that it be supplemented with current knowledge based on past experience of the effects of different maintenance activities on bridge condition.

APPLICATION

Legislative Appropriations

State and local appropriations are based on competing requests from different governmental sectors and total available funds. Each sector presents warrants to justify its budget request. Considered will be public safety, societal goals, economics, and opportunities to gain federal assistance. The sector having the best factually based, objectively presented, and readily understood indicators of cost and public benefits will gain the most sympathetic reception.

The methodology created to evaluate the consequences of maintenance service levels provides maintenance administrators with a tool to generate a quantitative set of facts to support budget requests. Both maintenance service levels and terminal serviceability options can be investigated for various budget scenarios. The resulting costs in terms of future budgetary requirements for the agency can be shown for different appropriation levels. Furthermore, the consequences to the taxpayer can be illustrated in terms of user costs, accident risk, inconvenience, and environmental impacts.

This ability to quantify the undesirable consequences of inadequate maintenance and rehabilitation funding permits maintenance managers to formulate effective presentations to legislative bodies. The request for budget sufficiency can now be thoroughly objective and increases the probability that the maintenance organization will be successful in their funding request.

Budgeting

Maintenance organizations frequently bear the brunt of budget cuts because the effects of maintenance reductions are not always immediately observable. This, of course, represents a narrow viewpoint on the part of administrators responsible for such reduction.

The study methodologies can be used by maintenance organizations to examine the long-term agency costs of setting different service levels. These analyses can be made by type of pavement subject to different traffic and environment. Maintenance service levels can be selected to minimize long-term costs within current financial constraints and thereby provide a basis for annual maintenance budgets and programs. The analytical process can be expanded to include an assessment of user costs and other public impacts. This factual information can be assembled and presented to government authorities who control funds for increase budgets.

Maintenance managers can use this factual information to demonstrate the adverse effects of maintenance budget cuts on preservation of investment. The methodology, therefore, represents a tool that maintenance managers can use to protect existing funds and argue for increases.

Maintenance Management

Maintenance management systems have budgeting procedures that depend on workload estimates by maintenance activity. Pavement and bridge maintenance activities depend not only on pavement and bridge conditions, but also on maintenance service levels. With an objective procedure to assist in selecting service levels, the workload estimating process is enhanced. This improves the highway maintenance organizations' ability to budget those funds intended to be used to preserve investment, and plan and program annual pavement and bridge maintenance activity.

Budgeting and Programming

Many organizations base their budget requests on expenditure histories, but some are able to predict maintenance requirements by maintenance element. Regardless, the methodology can be useful in determining increases or decreases in budget and program requirements to be associated with setting different maintenance service levels.

The program AGENCY predicts workload based on user-supplied maintenance service level specifications. Current pavement maintenance levels can be specified for the activities handled by the program. These activities include all pavement preventive maintenance treatments and activities that correct conditions in the pavement surface that evolve as the pavement deteriorates. The program outputs the quantity of each activity on an annual basis. For each pavement category being examined, this reflects the expected pavement maintenance workload over its entire service life. When a state has detailed expenditure information by pavement category and condition, the program inputs can be altered to calibrate the model to produce the workload quantities matching the agency's expenditure history. Once calibrated, the workloads for any maintenance service level can be predicted.

Program AGENCY generates the annual workload for a pavement with specified characteristics subject to a defined environment and given traffic. To evaluate maintenance service levels, a traffic growth factor is specified. This factor can be made unity. The resulting annual outputs now reflect the work expected to be generated by the category of pavement specified and for all conditions of the pavement subject to one level of traffic.

Any pavement category and traffic level can be evaluated. Produced for the maintenance manager is the annual workload by activity for each category, traffic level, and pavement condition.

A total work program is created by summing this workload for all pavement mileage in each category and by jurisdiction. Many organizations verify the validity of work programs by having them reviewed by the field supervisor in each jurisdictional unit. The supervisors evaluate the proposed program with respect to actual road conditions and recommend modifications as needed to achieve the maintenance levels proposed by top management.

When maintenance organizations budget by objective based on historical records or previous year expenditure levels, there is a direct tie to maintenance levels. Historical expenditures reflect previous year programs, and the current condition of the network can be assessed to define currently achieved maintenance levels. These levels can be specified as program inputs to generate reference workloads. The workload can be transformed directly into a budget by object using maintenance performance standards. These define work accomplishment rates for each activity and the labor, equipment, and material needed to complete a unit of work. Therefore, the resources required for each unit of workload can be directly computed. Performing this computation converts workload into units of labor, equipment, and material. These units can then be expressed in financial terms by applying unit costs to the labor, equipment, and material units. When the workload for an existing maintenance level is divided into the workload generated for any other specified maintenance level, a ratio is created. This ratio can be used to factor historical expenditures to produce the program and budget needed to achieve any specified maintenance level.

Work Scheduling

The execution of maintenance work is done by field crews or by maintenance contract. In either case, work is scheduled for particular roads based on their condition. A valuable output of this study on maintenance is the definition of the objective measures with which to specify maintenance service levels. Once management has specified the maintenance service levels to be achieved, the field manager is able to translate these specifications into a specific course of action.

The first step is a visual inspection of the highway's condition. Next, pavement sections are identified where threshold condition exceeds those specified in the maintenance service level guides. With this information, the field supervisor is prepared to recommend road sections for specific action, be it by contract or force account maintenance.

Work quantities are estimated for maintenance contracts or converted into labor, equipment, and material units using performance standards for force account programs. Timetables for work are prepared by balancing requirements against available resources.

Advantages of the Methodology

The major advantage of the pavement methodology is that it is an objective evaluation that can be used to examine the consequences of alternative maintenance service levels.

The methodology requires that maintenance service levels be objectively defined. If management elects to define their management program based on the use of the methodology, they are able to establish maintenance level guides that are presented in terms of maintenance element threshold conditions. Compliance with these guides by field personnel provides maintenance uniformity. Furthermore, by defining maintenance service levels in objective terms, it is possible to examine maintenance elements and determine the maintenance service levels that are being achieved by a highway maintenance organization.

The output of using the methodology is a quantitative estimate of the impact of different maintenance service levels on various considerations (e.g., safety in construction zones, roughness agency costs, vehicle operating costs). These objectively based evaluations of impact can be used to improve the results of the maintenance level of service methodology outlined in *NCHRP Report 223* (*17*) because quantitative measures of impact can be substituted for the consequences that are presently subjectively determined. The major value of *Report 223* then lies with the systematic assessment of value judgment that produces nonarbitrary and consistent relative weights for different considerations.

For evaluation the program AGENCY accepts categories of pavement in any initial condition. This permits the user to examine the consequences of different maintenance strategies for pavements near the end of their service life. The actions that are the most beneficial to the agency will not be the same at the end of a pavement's life as compared or contrasted to a new pavement.

The program AGENCY can be used to evaluate hypothetical maintenance treatments. The analyst can propose a treatment that will extend pavement life a certain number of years. The annualized costs savings in contrast to existing practices provide guidance on the amount that can be invested in developing and implementing new maintenance techniques.

The pavement methodology, although designed to assess the consequences of delaying maintenance, can also be used to select maintenance service levels that minimize agency costs or user impacts, i.e., preserve investment. In many respects, this is the more valuable of the two uses because identifying minimum cost maintenance strategies should be an agency goal. Also, the adverse consequences of deviating from some optimum level will exceed those of lesser strategies and thereby provide greater warrants for desired programs.

The principal strength of the bridge evaluation methodology lies in the structured systematic approach. It offers maintenance officials ways to determine the effects of specific maintenance activities on changes in bridge condition, as well as to compare the life-cycle costs associated with alternative construction and maintenance options.

Disadvantages of the Methodology

Program AGENCY is based on damage models developed from limited data bases. Although these are the best models available at this time, they may be questioned with respect to accuracy, particularly for certain regions of the country. As better information is developed through long-term pavement performance studies, improved damage models will become available. The incorporation of these improved models into the program will make it a more reliable and accurate tool.

The program "BLCCA" requires the user to estimate the effectiveness and costs of all maintenance treatments on bridge life. Little quantitative information exists to guide this process. Consequently, the analysis must be subjectively based at present.

Ease of Implementation

An objective of this study was to produce a methodology that would be implemented by highway maintenance organizations. Consequently, the computer programs were kept simple, designed for use on microcomputers, and made user friendly for the potential user who was envisioned as a young engineer familiar with microcomputers.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

The value of having a methodology to evaluate maintenance strategies is in being able to influence maintenance budget decisions. Highway budget appropriations are determined by legislators using guides from executive government entities and highway administrators. To get their fair share of available funds highway maintenance groups require factual, objectively based presentations that define the consequences to the tax payer and highway user of not providing needed maintenance. Subjective assessments of the adverse consequences will not attract the necessary support. What is needed is a factually based methodology that quantifies consequences in simple, understandable, objectively based terms.

The factually based, underlying relationships needed for the required methodology to preserve investment are not adequately defined. Better models are needed to predict maintenance element performance. The data base permitting these models to be formulated does not exist. Without such models it is not possible to make an objective evaluation of the consequences of setting different maintenance service levels or executing different maintenance treatments.

The maintenance levels being achieved on highways is reflected in the condition of maintenance elements over time. The

National Bridge inspection program and pavement management systems are developing condition information, but it is largely subjective. This condition information when collected at the network level over time permits gross assessments to be made of the relationship between maintenance expenditures and maintenance service levels. However, this data base is not precise enough to define the relationship between specific maintenance treatments and timing on subsequent maintenance element performance. This was demonstrated in analyzing the Nevada Department of Transportation data base on maintenance expenditures and pavement conditions.

Needed are uniform and accurate measures of maintenance element condition over time. This condition data, together with corresponding information that characterizes the maintenance element, quantifies its exposure to climatic and traffic influences, and documents all maintenance or rehabilitation treatments with respect to type, extent and timing, will provide the data base that can be analyzed to create maintenance element performance models.

Establishing such a data base requires a coordinated effort on the part of highway agencies. This effort can only be achieved through a structured program of research that is managed by some central organization with a long-term commitment of funds.

Data Availability

A major problem that needs to be addressed before selecting the data to be collected in any long-term monitoring effort is the availability of maintenance element characterization information. The researchers were assured by all of the highway agencies who cooperated with them in establishing monitoring sites that information on pavement construction, rehabilitation, and other improvements could be found to characterize pavement layer materials and thicknesses. In some states, the pavements had to be limited to new construction because the effort to develop historical characterization information on older rehabilitated pavements appeared quite substantial. In almost all cases, it proved far more difficult to obtain this information than envisioned by the states. They found that their records were neither uniform nor consolidated. In some cases, the only way to develop reliable information was through pavement coring. This experience suggests that trial data extraction procedures be implemented before resource commitments are made, particularly before monitoring old pavement sections in any state. The simplest approach is to confine pavement monitoring to unrehabilitated pavement sections. These pavements reflect current design standards. The effect of different maintenance treatments in extending their service life can be more readily established.

The reasons cited for poor record continuity included personnel transfers, modified record-keeping procedures, and top administrative policy changes on the emphasis and resources allocated to the record-keeping process.

User Costs

Questions are continually raised concerning the role that user costs and other non-agencies costs should play in determining maintenance policy. Should priority be given to roads that provide a poor ride, or to those that are in danger of becoming structurally unsound? The major concern of highway agencies should be spending available funds in a cost-effective manner. This means "maximizing the public good," whatever this may be. However, it is clear that this does not mean maximizing the "good" of the highway agency. Public moneys must provide maximum benefits to the public. This is accomplished by minimizing both agency and user costs, plus other adverse impacts to the motorist, including discomfort, inconvenience, accidents and, to the public, pollution and noise.

Since all these consequences are legitimate concerns, they should be considered in any decision process. Therefore, all consequences of a given maintenance strategy should be compiled and weighed as part of evaluation process that precedes policy decisions on the particular maintenance strategy to adopt.

Pavement Methodology

The program "AGENCY" computes maintenance workload by predicting the pavement's condition, quantifying the pavement condition threshold that generates a maintenance response, and defining the extent of the condition that will be corrected. These corrective and preventive maintenance actions alter pavement condition and performance. Consequently, they define the maintenance service levels achieved. To use the methodology, maintenance organizations must specify, in objective terms, maintenance service level thresholds and the extent of maintenance.

If programs and budgets are to be based on the resulting estimates of workload, quantitative guides must be disseminated to field personnel. Otherwise, the programs and budgets will not accomplish their intended purpose. Once this is done, maintenance field forces must follow the guides to ensure that work is performed in accordance with the guides. Otherwise, the programming will not accomplish the levels sought by management, and, possibly of more concern, lack of adherence to policy guides can in the presence of accidents create a tort action against the highway agency.

Unless a preventive maintenance program is active, there is little to gain by implementing such a program once the effects of weathering and traffic have taken their toll on a maintenance element. The prudent course of action is to perform the minimum amount of corrective maintenance needed to keep the maintenance element safe and serviceable. Top priority should be given to rehabilitation to minimize continuing maintenance investments. Once the element's service life has been restored, then consider the best preventive program to minimize life-cycle costs and impacts for the next life cycle.

Bridge Methodology

Developing an objective evaluation methodology to assess the consequences of different maintenance strategies for bridges proved more difficult than for pavements. There are a number of reasons. First, whereas a pavement is a single maintenance element, a bridge is a complex entity consisting of many maintenance elements within each of its three principle components, i.e., deck, superstructure, and substructure. Defining the effectiveness of maintenance requires an assessment of a maintenance element condition both prior to and following any maintenance treatment. For a bridge, this represents objectively based evaluations of conditions for many elements. More importantly, a maintenance treatment needs to be associated with each maintenance element. Highway agency bridge expenditures are only 3 to 5 percent of those recorded on pavements. Consequently, maintenance organizations consolidate bridge treatments into broad activity categories. No record is ever made of specific treatments to specific elements and the required cause and effect data base is never created.

An objective assessment of the impact of maintenance means selecting a bridge maintenance element and developing specific information on its condition over time. It further means establishing a record of treatments to that element. Candidate elements are those generating major bridge maintenance expenditures that include the bridge approach slab, the deck and structural steel.

Data Adequacy

Bridge data arising from current state reporting procedures are inadequate because the maintenance expenditures are recorded in broad categories. The example state, NCDOT, used more expenditure categories than most other states. Nonetheless, its categories were too broad to compare the cost effectiveness of specific maintenance activities. If the objective of the evaluation methodology were to compare the cost effectiveness or contribution to life expectancy of two different maintenance activities, such as painting or paving, the use of broad categories would not be a problem. However, the objective was to compare the consequences of performing different amounts or levels of the same activity. The concern is not whether to pave or paint but whether to patch in year "A" or completely resurface in year "B" or whether to spot paint in year "X" or completely paint in year "Y."

Broad maintenance expenditure categories do not permit one to answer these questions empirically. Accordingly, more specific categories must be employed in recording bridge maintenance expenditures if relationships between service levels and performance are to be obtained.

Individual maintenance activities are usually directed at only one bridge component (superstructure, substructure, or deck). To analyze maintenance's influence on the condition of any of these three components requires component age. Frequently the SI&A Bridge Files show bridges as having been reconstructed when they are only partially reconstructed. Consequently, neither the initial construction date nor the reconstruction date in SI&A records is an accurate reflection of bridge component age. To overcome this problem, it is recommended that separate construction dates be recorded for a bridge deck, the superstructure, and the substructure.

Data-Base Development

Structure inventory and appraisal data constitute a valuable resource for bridge maintenance officials attempting to allocate maintenance resources in a cost-effective manner. They represent a systematic and relatively comprehensive data-collection effort that provides bridge officials with a wealth of information for monitoring the condition of performance of entire bridge inventories. However, SI&A data can tell maintenance officials nothing about the cost effectiveness of alternative maintenance strategies. Also needed are maintenance expenditure data. Accordingly, it is recommended that both inspection and all maintenance expenditure data be combined in a single data base. Alternately unique bridge identification numbers can be assigned to all bridge records for each structure in a state's inventory. This will facilitate the integration of data from separate data bases such as the SI&A files, maintenance expenditure files, and contract maintenance files. Ideally, these records should also include the initial construction cost of each structure in the inventory.

SUGGESTED RESEARCH

The relationships between a maintenance treatment and the subsequent performance of a maintenance element cannot be quantitatively defined at this time. Such relationships are needed before maintenance service levels can be objectively evaluated.

Highway pavement and bridge maintenance were addressed in this study. A large number of maintenance conditions were examined. For each condition a large number of maintenance treatments were identified. Research to establish a data base that could be used in determining the desired relationships for all conditions and treatments is unthinkable. The expense would be enormous and the potential benefits would not justify this effort. There are, however, a limited number of maintenance elements and treatment options that justify further study. These are the maintenance elements responsible for major maintenance expenditures and the treatments that most influence agency cost and user impacts during the life of the maintenance element.

The maintenance element generating the most expenditures is the highway pavement. Pavements are divided into flexible and rigid. The mileage of flexible pavements exceeds that of the rigid. Because there is more flexible pavement mileage, there are more maintenance expenditures. Therefore, flexible pavements are the top maintenance element candidate to study in developing relationships between condition, treatment, and performance.

Maintenance activities fall into two categories, preventive and corrective. Preventive activities offer the most potential for maintenance expenditure savings and are subject to the widest variation in practice. Understanding the influence of the timing and extent of different preventive maintenance treatments on flexible pavements offers the most potential benefit from further research.

Other candidates offering savings include flexible pavement crack sealing, rigid pavement joint and crack sealing, bridge slab approach undersealing, and steel painting.

To produce an effective data base for further analysis, the information generated must include:

1. Characterization of the maintenance element at a defined location.
2. Uniform and accurate measures of the element's condition at intervals and just prior to any maintenance treatment.
3. Traffic and climate data.
4. Accurate measures of the extent and timing of any maintenance treatment.
5. Description of the materials and procedure used in any maintenance treatment.
6. Measures of the element's condition following any maintenance treatment.

REFERENCES

1. Federal Highway Administration, U.S. Department of Transportation. "Highway Statistics 1978–1982."
2. "Highway Bridge Replacement and Rehabilitation Program." Fifth Annual Report of the Secretary of Transportation, Government Printing Office, Washington, D.C. (Oct. 1984).
3. BUTLER, B. C., JR., CARMICHAEL, R. F., III, FINN, F. N., AND HUDSON, W. R. "Evaluating Deferred Maintenance Strategies." Interim Report, NCHRP Project 14-6 (Dec. 1982).
4. BUTLER, B. C., JR., "Economic Analysis of Roadway Occupancy for Freeway Maintenance and Rehabilitation." Federal Highway Administration Report, *FHWA-RD-76-14* (Oct. 1974).
5. MARKOW, M. J., AND BRADEMEYER, B. D., "EAROMAR Version 2." Final Technical Report, Federal Highway Administration, *FHWA/RD-82/086* (Apr. 1984).
6. LEWIS, R. M., "Practical Guidelines for Minimizing Tort Liability." *NCHRP Synthesis of Highway Practice 106* (1983) 40 pp.
7. THOMAS, L. W., "Liability of State Highway Departments for Design, Construction, and Maintenance Defects." *NCHRP Research Results Digest 80* (Sept. 1975) 48 pp.
8. *Indian Towing Co. v. United States,* 350 U.S. 61, 76 S. Ct. 122, 100 L. ed 48 (1955).
9. *State v. Abbott,* 498 P. 2d 712 (Alaska 1972).
10. Empresa Brasileira de Planejamento de Transportes, GEIPOT, "Research on the Interrelationships Between Costs of Highway Construction Maintenance and Utilization." Final Report, UNDP Project BRA-74/102, Brasilia (1981).
11. *Highway Maintenance Performance Standards,* Alabama, Arizona, California, Connecticut, Delaware, Florida, Illinois, Iowa, Maine, Michigan, Minnesota, Nebraska, Nevada, New York, Ohio, Oklahoma, Pennsylvania, Rhode Island, South Dakota, Tennessee, Virginia, and Washington.
12. BYRD, TALLAMY, MACDONALD AND LEWIS, "Techniques for Reducing Roadway Occupancy During Routine Maintenance Activities." *NCHRP Report 161* (1975) 55 pp.
13. "Progress Report on Maintenance and Operations Personnel." *Transportation Research Circular 270* (Jan. 1984).
14. WINFREY, ROBLEY, "Highway Economics." Section 2, *Handbook of Highway Engineering,* Baker, Van Nostrand Reinhold Company, N.Y. (1975).
15. HUDSON, W. R., HAAS, R., AND PEDIGO, R. D., "Pavement Management System Development." *NCHRP Report 215* (1979) 32 pp.
16. IVEY, D. L., GRIFFIN, L. I., III, WAMBOLD, J. C., ZIMMER, R. A., AND ROSS, H. E., JR., "Influence of Roadway Surface Discontinuities on Safety." Committee AC-B07, Transportation Research Board (1984).
17. KULKARNI, R., FINN, F., GOLABI, K., JOHNSON, R., AND ALVITI, E., "Maintenance Levels-of-Service Guidelines." *NCHRP Report 223* (June 1980) 118 pp.

APPENDIX A

TEST PAVEMENT DATA COLLECTION

A major requirement of the life-cycle methodology is the ability to predict a maintenance element's performance following a maintenance treatment. Studies show that this performance depends on both the treatment and the condition of the maintenance element at the time of the treatment (Refs. *A-1, A-2, A-3*). The research was unable to find quantitative information or a data base relating maintenance element performance to existing condition, maintenance treatment, and the environment. Because such relationships are the key to creating a credible methodology, a major commitment of project time and resources was directed towards establishing a primary data base that could be used to determine these required relationships.*

Many types of pavement distress receive maintenance treatments. It is desirable to have information on the performance of various pavement types following the correction of all types

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* A copy of the cracking maps and other data relating to the test sections evaluated during this project is available on a loan basis from the Director, Cooperative Research Programs. Request Volume 3 of the Draft Final Report, NCHRP Project 14-6, "Evaluating Deferred Maintenance Strategies."

of distress using a variety of maintenance treatment alternatives. This was not a practical study objective. A study of such magnitude required resources beyond those available to this effort. Consequently, a limited study was initiated. A data base was sought that would permit equations to be developed to predict the effect of different maintenance treatments in retarding the evolution of flexible pavement fatigue cracking.

This particular distress was selected because: (1) Flexible pavement fatigue cracking is a major distress problem. (2) Fatigue cracking generates a variety of different maintenance treatments. (3) The maintenance activities executed to retard or correct fatigue cracking represent a major portion of the resources expended by maintenance organizations.

A procedure for measuring and monitoring fatigue cracking was developed to create a data base. The procedure required locating a number of test sections and performing a detailed fatigue cracking evaluation. The detailed evaluation included mapping all the cracks in a section, classifying their severity, and photographing representative cracking.

A statistically designed experiment was formulated to guide the fatigue cracking study. The design factorial is shown in Figure A-1. Test locations were sought covering the environmental regions defined by the Thornthwaite climatic zones. Other constraints were project resources and time. A sample size of 18 was set as the minimum in each state for analysis purposes and enlarged to 24 sections to accommodate attrition.

Guides developed to select test locations in each state are outlined in the procedure manual shown in Figure A-2. Copies of the manual were sent to all cooperating states who were requested to tentatively identify roads that were candidates for establishing test locations.

The researchers met with state personnel to review the scope of work. In personal discussions the following was established: (1) the availability of historical pavement characterization data including a construction and rehabilitation history; and (2) candidate routes and sections where pavements were presently evidencing fatigue distress.

Subgrade	Traffic	Volume
	Low	High
Good		
Poor		

Figure A-1. Design factorial used to guide the selection of flexible pavement sections showing fatigue cracks.

Once a routing of tentative locations had been identified, the concerned districts or residences were notified that the project staff would be mapping their road surface conditions. The project staff also received the names of area personnel who could be contacted for detailed information on section construction and maintenance. Most states assigned someone to work with the staff in locating and mapping sections. This served two purposes. First, it was possible to locate and map the roads more quickly and, second, the state learned the study mapping procedures first hand so they were prepared to conduct ratings in subsequent years.

Test sections were located by driving slowly along suggested portions of a road until an area of uniform distress representative of the pavement's condition was located. The information on the section locator forms (see Fig. A-3) includes mileposts, distance from intersecting highways, direction of lane used for pavement section, and outstanding landmarks nearby. A map of the section was also drawn.

Twenty test section panels were established by laying out a 100-ft tape marked at 5-ft intervals along the side of the road. Each panel was numbered consecutively 1–20. The beginning and end of the section was marked with a washer held to the pavement by a nail. The width of the pavement and shoulder was measured, and an outside edge was established for a reference line for the section. In most cases the edge was 12 ft from the centerline. If the pavement was wider or narrower than 12 ft, this was noted on the form and the edge established accordingly. The washers at each end of the section also marked the pavement edge.

Each section's pavement distress was classified by its appropriate severity level (low, moderate, or high) and area of each distress in square feet. This information was indicated on the form shown in Figure A-4 and was based on the pavement rating standards found in the "Highway Pavement Distress Identification Manual" (Ref. *A-4*).

Section photographs were taken to get a more precise measurement of the severity and extent of cracking. A panel, representative of the distress severity of the entire section, was photographed. Three photos were taken of the panel at different angles with different lenses to get a good representation of the condition of the section. A name plate with the state, section, and panel number was included in the photograph.

The area of fatigue cracking was marked with a lumber crayon and the distance of this cracking from the established edge was measured. The area of cracking was measured and the level of severity (low, moderate or high) estimated. This information was drawn on the section locator map shown in Figure A-5. To distinguish the different severity levels colored pencils were used: blue denoted low severity, green denoted medium, and red denoted high. This same procedure was followed for representing individual cracks, potholes, and patches on the grid. Panels were mapped one at a time to improve accuracy.

The cracking maps were reduced the percent of pavement area cracked for each severity level. All single cracks were converted to cracking area by equating 3 lineal feet of single-cracks to 1 sq ft of area. These data, as calculated by severity level, panel, and section, were summarized in the form shown in Figure A-6.

Pavement characterization data were obtained and included serviceability, pavement layer information, environmental data (precipitation, freezing index, etc.) and traffic data (ADT, % trucks, accumulated EALS).

PROCEDURAL MANUAL FOR PAVEMENT CONDITION STUDY

Information is needed on the performance of highway pavements following different maintenance treatments. This information, assembled under controlled procedures, does not exist. The purpose of this pavement condition study is to develop this information.

It would be desirable to develop information on the performance of various pavement types with each type of distress, following all maintenance treatment alternatives. This is not a practical objective since the resources required for a study of this magnitude are not available. Consequently, this pavement condition study is more limited in scope.

Our objective is a data base that will permit equations to be developed to predict the effects of different maintenance treatments in retarding the evolution of flexible pavement fatigue cracking (alligator cracking). We have selected this particular distress because:

1. Flexible pavement fatigue cracking is a major distress problem.
2. Fatigue cracking generates a variety of different maintenance treatments.
3. The maintenance activities executed to retard or correct fatigue cracking represent a major portion of the resources expended by maintenance organizations.

Other distress types can influence or indicate the causes of the fatigue cracking. Therefore, a record of all observable distress is needed each time a test section is evaluated and the form on which this is to be shown is illustrated in Exhibit A.

This manual was developed to standardize the data collection procedure. It includes severity level definitions for all distresses listed on the evaluation form (Exhibit A), and photographic examples of fatigue cracking for severities 1 through 9 (1-3 low, 4-6 moderate, 7-9 high)(Exhibit B). The manual includes locator maps for each section in your state. These locator maps should be updated with any relevant changes. We envision that these data will be used by state, federal, and other research organizations. Up-to-date maps will aide them in finding the sections.

The manual includes distress maps for each of your sections. Please use these maps for drawing updated maps. This will permit an evaluation of the progression of distress.

After each evaluation cycle, please send updated distress forms and section maps to ARE, Inc. at the following address:

ARE Inc
2600 Dellana Lane
Austin, TX 78746

We will update the masters, reduce the data, and return copies of the updated material to be used for the next cycle.

Evaluation Procedure

A section consists of a 100' long by one lane wide area that has been divided into twenty segments, each five feet long. The distress covering the entire 100' section needs to be classified, measured, and recorded according to the procedure outlined below:

Figure A-2. Procedural manual for pavement condition study.

A. Locate Section

1. Where possible, sections coincide with mile posts or other state markers, these should help narrow your search.
2. If the section does not coincide with one of these markers, use the landmarks on the "Location Maps".
3. The beginning and end of each section is marked with a washer held to the pavement by a masonry nail (see exhibit B).
4. If any nails are missing, or covered, try and locate the section using landmarks and distress patterns (if any). Be sure to note on the mapping form that a washer was missing and re-established.

B. Mark and Evaluate the Pavement

1. Establish Outside Edge Reference Line for Section

   The outside edge of the section should be determined and a center or lane line indicated on the mapping form. If the roadway is wide, the edge should be established at 12 feet from the lane dividing line. If the lane is less than 12 feet wide, the drawn center of lane line should reflect this.

2. Mark Section

   Mark the 100 foot section using a tape measure. Mark the section at 5 foot intervals along the outside edge with a lumber crayon line extending about 12 inches into the section. Number each panel consecutively 1 through 20 in the lower right hand corner.

3. Document all Section Distresses

   Classify and measure all distress covering the entire 100 foot section and record on the form shown in Exhibit A. Use the following procedure:

   a. Fill in header information.

   b. Rate the top set of distresses by measuring or estimating (if necessary) the area of each in square feet, and entering this measure under the appropriate severity level column. L stands for low severity, M for medium, and H for high severity level distresses.

   c. Rate the bottom set of distresses by measuring or estimating their lengths in linear feet and entering them under the appropriate severity level column.

Distress severity levels have been derived from the "Highway Pavement Distress Identification Manual" [Ref. 1] and the "Development of a Pavement Condition Rating Procedure for Roads, Streets and Parking Lots" [Ref. 2], and are included below:

Name of Distress: <u>Bleeding</u>

Description: Bleeding is a film of bituminous material on the pavement surface which creates a shiny, glass-like, reflecting surface that usually becomes quite sticky.

Severity Levels: No degrees of severity are defined. Bleeding should be noted when it is extensive enough to cause a reduction in skid resistance.

How to Measure: Bleeding is measured in square feet of surface area.

Name of Distress: <u>Block Cracking</u>

Description: Block cracks divide the asphalt surface into approximately <u>rectangular</u> pieces. The blocks range in size from approximately 1 ft.^{2} to 100 ft.^{2} (.09 m^2 to 9m^2) Cracks that break the pavement into larger blocks are generally rated as longitudinal and transverse cracking. This type of distress differs from alligator cracking in that alligator cracks form smaller, many-sided pieces with sharp angles.

Severity Levels: L - Blocks are defined by (1) nonsealed cracks that are nonspalled (sides of the crack are vertical)

Figure A-2. Continued

or only minor spalling with a 1/4 in. (6 mm) or less mean width; or (2) sealed cracks have a sealant in satisfactory condition to prevent moisture infiltration.

M - Blocks are defined by either (1) sealed or nonsealed cracks that are moderately spalled; (2) nonsealed cracks that are not spalled or have only minor spalling, but have a mean width greater than approximately 1/4 in. (6 mm) or (3) sealed cracks that are not spalled or have only minor spalling, but have sealant in unsatisfactory condition.

H - Blocks are well-defined by cracks that are severly spalled.

How to Measure: Block cracking is measured in square feet of surface area. It usually occurs at one severity level in a given pavement section; however, any areas of the pavement section having distinctly different levels of severity should be measured and recorded separately.

Name of Distress: <u>Corrugation</u>

Description: Corrugation (also known as washboarding) is a series of closely spaced ridges and valleys (ripples) occurring at fairly regular intervals-usually less than 10 ft. (3 m) along the pavement. The ridges are perpendicular to the traffic direction. If bumps occur in a series of less than 10 ft. (3 m), due to any cause, the distress is considered corrugation.

Severity Levels

L - Corrugation produces low-severity ride quality deterioration.

L - Low severity level
M - Medium severity level
H - High severity level

M - Corrugation produces medium-severity ride quality deterioration.

H - Corrugation produces high-severity ride quality deterioration.

How to Measure: Corrugation is measured in square feet of surface area.

Name of Distress: <u>Depression</u>

Description: Localized pavement surface areas with elevations slightly lower than those of the surrounding pavement are called depressions. In many instances, light depressions are not noticeable until after a rain, when ponding water creates "birdbath" areas; on dry pavement, depressions can be spotted by looking for stains caused by ponding water.

Sags, unlike depressions, are abrupt drops in elevations.

Severity Levels: Maximum Depth of Depression

L - 1/2 to 1 in. (13 to 25 mm)
M - 1 to 2 in. (25 to 51 mm)
H - more than 2 in. (51 mm)

How to Measure: Depressions are measured in square feet of surface area.

Name of Distress: <u>Rutting</u>

Description: A rut is a surface depression in the wheel paths. Pavement uplift may occur along the sides of the rut; however, in many instances ruts are noticeable only after a rainfall, when the wheel paths are filled with water.

Severity Levels:

L - 1/4 - 1/2 in. (6 - 13 mm)
M - >1/2 - 1 in. (13 - 25 mm)
H - >1 in. (> 25 mm)

Figure A-2. Continued

How to Measure: Rutting is measured in square feet of surface area, and its severity is determined by the mean depth of the rut. To determine the mean rut depth, a straightedge should be laid across the rut and the maximum depth measured. The mean depth should be computed from measurements taken along the length of the rut.

Name of Distress: Shoving

Description: Shoving is a permanent, longitudinal displacement of a localized area of the pavement surface.

Severity Levels:
L - Shove causes low-severity ride quality deterioration.
M - Shove causes medium-severity ride quality deterioration.
H - Shove causes high-severity ride quality deterioration.

How to Measure: Shoves are measured in square feet of surface area.

Name of Distress: Slippage Cracking

Description: Slippage cracks are crescent or half-moon shaped cracks generally having two ends pointed into the direction of traffic.

Severity Levels: No degrees of severity are defined. It is sufficient to indicate that a slippage crack exists.

How to Measure: Slippage cracking is measured in square feet of surface area.

Name of Distress: Swelling

Description: Swell is characterized by an upward bulge in the pavement's surface - a long, gradual wave of more than 10 ft. (3 m) long. Swelling can be accompanied by surface cracking.

Severity Levels:
L - Swell causes low-severity ride quality deterioration. Low-severity swells are not always easy to see, but can be detected by driving at the speed limit over the pavement section. An upward acceleration will occur at the swell if it is present.
M - Swell causes medium-severity ride quality deterioration.
H - Swell causes high-severity ride quality deterioration.

How to Measure: The surface area of the swell is measured in square feet.

Name of Distress: Edge Cracking

Description: Edge cracks are parallel to and usually within 1 to 2 ft. (.3 to .6 m) of the outer edge of the pavement. The area between the crack and pavement edge is classified as raveled if it breaks up (sometimes it breaks up to the extent that pieces are removed).

Severity Levels:
L - Low or medium cracking with no breakup or raveling.
M - Medium cracks with some breakup and raveling.
H - Considerable breakup or raveling along the edge.

How to Measure: Edge cracking is measured in linear feet.

Name of Distress: Lane/Shoulder Drop Off

Description: Lane/Shoulder drop off is a difference in elevation between the pavement edge and the shoulder.

Severity Levels:
L - The difference in elevation between the pavement edge and shoulder is 1 to 2 in. (25 to 51 mm).
M - The difference in elevation is over 2 to 4 in. (51 to 102 mm).

Figure A-2. Continued

H - The difference in elevation is greater than 4 in. (102 mm).

How to Measure: Lane/Shoulder drop off is measured in linear feet.

4. Detailed Mapping Procedure

A detailed mapping of all fatigue cracking, patches, and potholes over the entire section should be made. The forms used to map the fatigue cracking for a section consist of five sheets of special grid paper, as shown in Exhibit B. Each sheet contains a grid depicting four 5 foot long panels of the 100 foot long section. The grid depicts a lane width of 12 feet.

If the lane being mapped is less than 12 feet wide, the appropriate number of top rows of the grid should be marked off the form to show the actual width.

Once the section is marked and the edge defined, a detailed map of the fatigue cracking is developed using the following procedure:

a. Map the current cracking condition on the map provided from the last survey and show the progression of fatigue cracking and severity

b. Show all areas of fatigue cracking by marking the perimeters. A different color is to be used for each level of severity. Red is used for high severity, green for medium, and blue for low severity.

c. Show individual cracks in color code when no pattern or area has evolved. An area of cracking is assumed when there is a minimum concentration of 3 cracks per square foot.

d. Show all patching by marking the perimeter with black. Crosshatch the area with color coding to show the quality of the patch. Use red for a badly deteriorated patch, green for moderately deteriorated, and blue for a good patch.

e. All potholes should be sketched on the map with a black perimeter.

Figure A-2. Continued

SECTION CHECK LIST

1. Locate road section using:
   a. Milepost or other marker
   b. Landmarks
   c. Washer and nail
   d. Crack pattern

2. Establish beginning and ending points with 100 foot tape, mark at least every five feet sector and probably every one foot.

3. Survey the pavement area and delineate the border of distress using lumber crayon or other marker.

4. Map the distress using a measure to determine exact distances out into the roadway.

5. List other distress on appropriate sheet relating to block cracks, ruts, etc.

6. Pick up tape and all other materials.

Figure A-2. Continued

REFERENCES

1. Smith, Roger E., M.I. Darter, S.M. Herrin, "Highway Distress Identification Manual for Highway Condition and Quality of Highway Construction Survey," FHWA, March 1979.

2. Shahin, M.Y., S.D. Kohn, "Development of a Pavement Condition Rating Procedure for Roads, Streets, and Parking Lots," Construction Engineering Research Laboratory, July 1979.

EXHIBIT A

PAVEMENT CONDITION STUDY

State ____________________ Section No. ____________

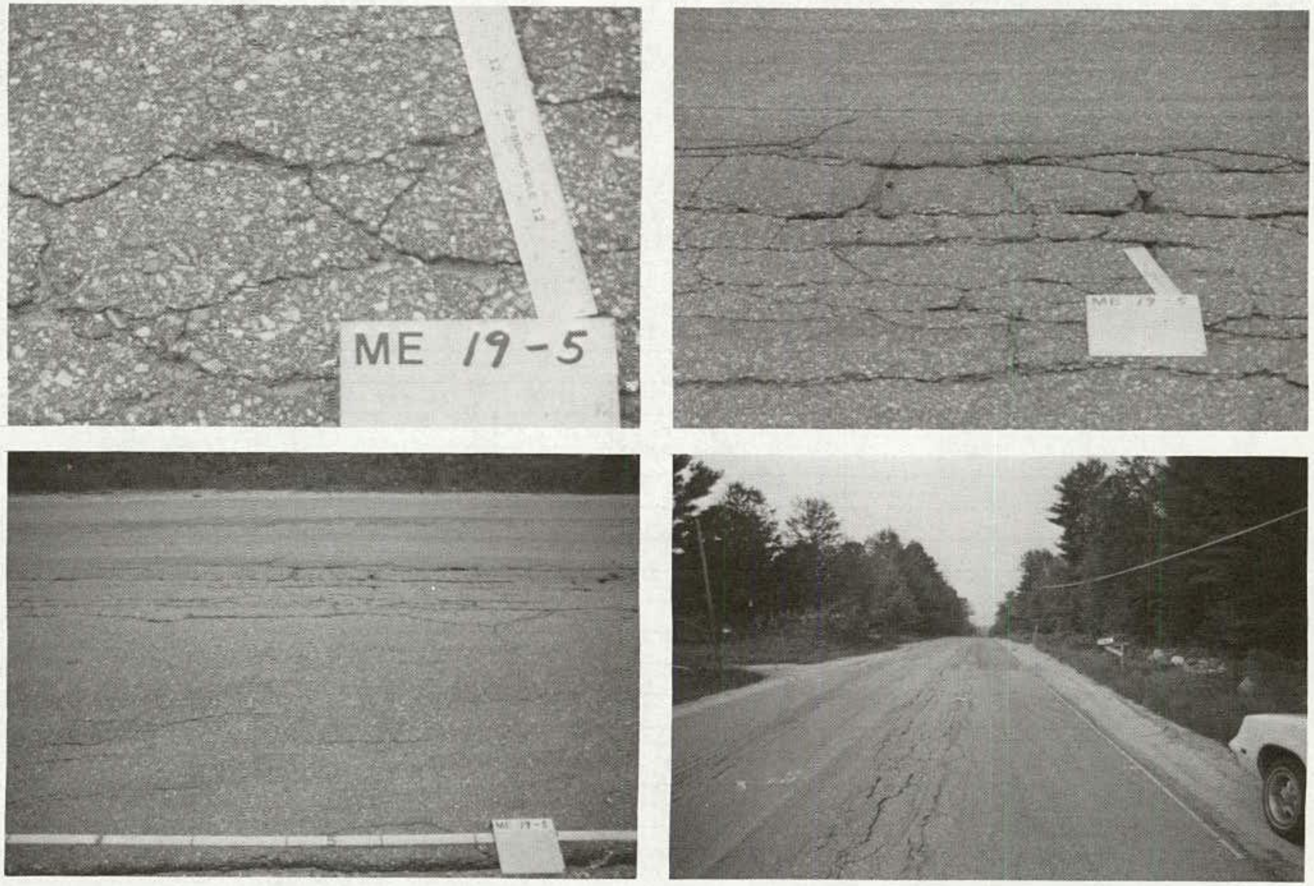
Date _____________________ Rater _________________

Distress	Square Feet			Comment
	L	M	H	
Bleeding				
Block Cracking				
Corrugation				
Depression				
Rutting				
Shoving				
Slippage Cracking				
Swelling				
		Lineal Feet		
Edge Cracking				
Lane/Shoulder Drop Off				

Exhibit A.

Figure A-2. Continued

EXHIBIT B



HIGH SEVERITY
LEVEL 8

Figure A-2. Continued

Project ______________________ Page __________

Section Locator Form

State ______________________ Date __________

County ______________________ Technician __________

Section # ______________________

Route Number ______________________

Direction of Lane ______________________

Intersecting Roads ______________________

Distance from closest intersecting road to test section:

Description of landmarks nearby:

Distance of landmark to test section:

Distance from outside edge to nail placed to mark start of section:

General description of pavement section (Pavement width, length, shoulder width, markings, severity levels, etc.):

Map area:

Figure A-3. Section locator form.

NCHRP PROJECT 14-6

Evaluating Deferred Maintenance Startegies

State ______________ Section No. ________

Date ______________ Rater ________

Distress	Square Feet			Comment
	L	M	H	
Bleeding				
Block Cracking				
Corrugation				
Depression				
Rutting				
Shoving				
Slippage Cracking				
Swelling				
		Lineal Feet		
Edge Cracking				
Lane/Shoulder Drop Off				

Figure A-4. Pavement distress form.

SECTION LOCATOR MAP

State ______________ **Section** ____________________ **Date** ___________________

Time ______ **AM** ______ **PM** **Sun** ☐ **No Sun** ☐

Temperature ____ **F** **Rater** _____________

Scale, ft. 3/8"= 1'

1 2 3 4

Note: Potholes to be filled in with correct severity level color.

LEGEND

Red – High Severity
Green – Medium Severity
Blue – Low Severity
Black – Outline of Road

ARE INC ARE Inc - ENGINEERING CONSULTANTS
2600 DELLANA LANE · AUSTIN, TEXAS · 78746

Figure A-5. Section locator map.

This information, with the percent cracking data, section locator forms and section locator maps was condensed as shown in Figure A-7. Sections were established and mapped in the ten states shown in Figure A-8.

All participating states agreed to update the condition maps annually before resources were committed to establish the sections in a given state. Thus, the section maps will be more valuable, following these annual updates, which will produce a detailed condition history to use in pavement performance modeling. Also the updates will produce data on the performance of the pavement sections following different maintenance treatments.

A second condition mapping has now been made in Texas and South Carolina. As expected, a number of sections received a maintenance treatment or overlay. Some time must pass, however, before distress will again be evident. The untreated sections showed distress evolution which varied widely. Table A-1 shows a comparison of total distress for the first and second mapping and the measured increase for each section. The data could not be analyzed and related to pavement characteristics and traffic because this information has not been received from South Carolina.

This is one problem encountered in establishing test sections. In each stae, the researchers stressed the need to define pavement characteristics for sections, and, without exception, the states expressed confidence that this information could be readily compiled. A limited number of states said that the required characterization data would only be readily accessed on newly constructed pavements and, in these cases, sections were limited to such new pavements.

Once states tried to compile the required characterization information, many discovered that their records were either inaccurate, incomplete, or missing. Consequently, there was considerable delay in developing characterization information on the test sections. Some of the information presented was defined as being estimates, and some states undertook to core their pavement sections to establish more reliable information.

The section data were of value to the study because the information helped one establish the distribution of cracking within a pavement section. This information was needed to simulate different spot seal and patching activities on flexible pavements.

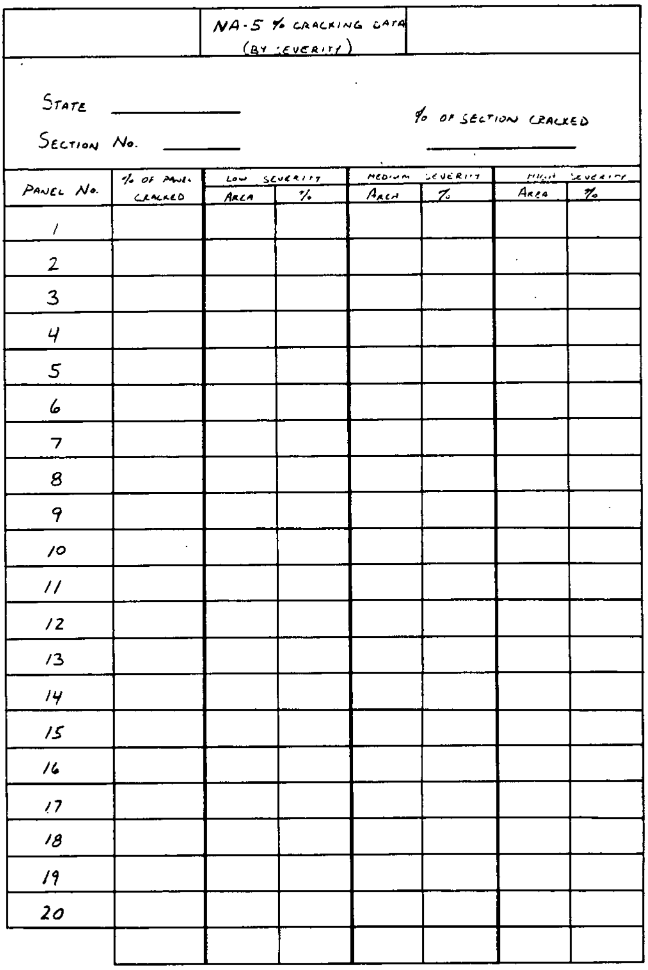
REFERENCES

A-1 Empresa Brasileira de Planejamento de Transportes—GEIPOT, "Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization." Final Report (1981). Volume 7, "Study of Pavement Maintenance and Deterioration." Brasilia (1982).

A-2 Phang, W. A., Blum, W., "Preventive Pavement Maintenance Concepts." Ministry of Transportation and Communications of Ontario (1980).

A-3 Vyce, J. M, "Bituminous Resurfacings on Flexible Pavements." *Research Report 31,* Engineering Research and Development Bureau, New York State Department of Transportation (Aug. 1975).

A-4 Smith, R. E., Darter, M. I., Herrin, S. M., "Highway Pavement Distress Identification Manual." Federal Highway Administration (Mar. 1979).



NA-5 % CRACKING DATA
(BY SEVERITY)

STATE ____________

SECTION No. ________

% OF SECTION CRACKED ____________

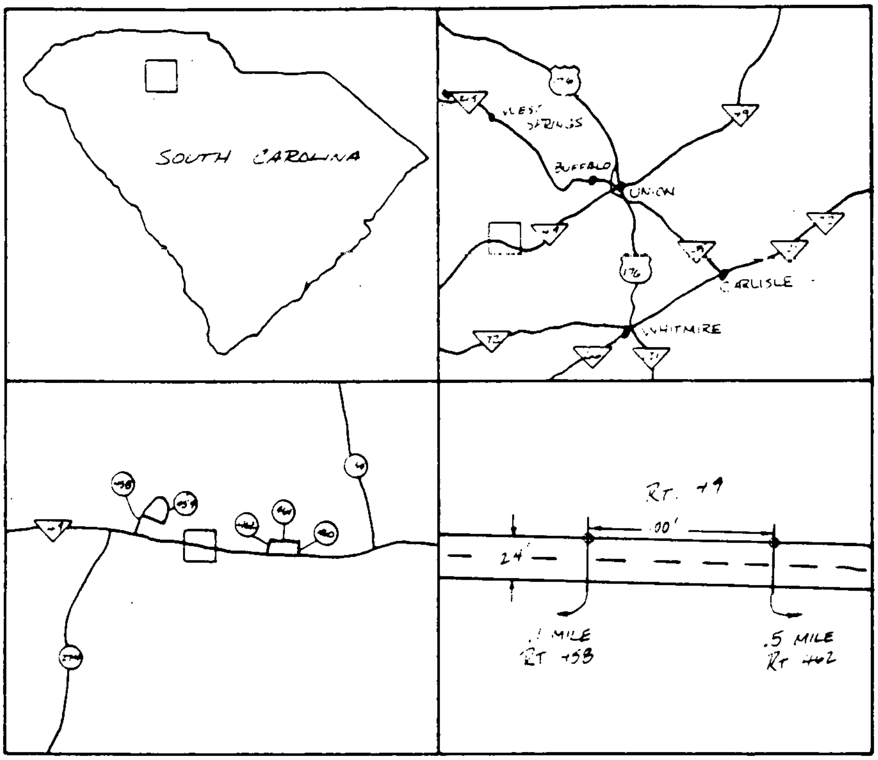
PANEL No.	% OF PANEL CRACKED	LOW SEVERITY		MEDIUM SEVERITY		HIGH SEVERITY	
		AREA	%	AREA	%	AREA	%
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

Figure A-6. Form for calculating percent of pavement area cracked.

Table A-1. Evolution of fatigue cracking on South Carolina test sections.

Section No.	Percent Pavement Area Cracked 1984	1985	Difference	Increase (%)
SC-1	5.0	7.6	2.6	52.0
SC-3	11.4	14.0	2.6	22.8
SC-4	23.6	31.6	8.0	33.9
SC-8	4.8	9.2	4.4	91.7
SC-9	30.6	33.4	2.8	9.1
SC-10	31.7	100.0	62.3	197.0
SC-14	32.9	35.0	2.1	6.4
SC-15	9.8	10.3	.5	5.1
SC-16	25.4	51.7	26.3	103.0
SC-17	29.1	33.0	3.9	13.0
SC-18	28.2	30.7	2.5	8.9
SC-19	11.3	16.8	5.5	48.7
SC-20	8.4	12.7	4.3	51.2
SC-21	65.1	66.7	1.6	2.5
SC-22	6.7	7.2	.5	7.5

```
SECTION   : SC-9
```



```
 ------------------------------
|                              |
| COUNTY    : UNION            |
| HIGHWAY   : S.R. 49          |
| MILEPOST  :                  |
| DIRECTION : W                |
| STATE ID  :                  |
|                              |
 ------------------------------

 ------------------------------
|                              |
| NUMBER OF LANES (1 WAY): 1   |
| WIDTH (FT.) - PAVEMENT : 12  |
|        - SHOULDER INNER :    |
|                  OUTER : U   |
|                              |
 ------------------------------

 ------------------------------
|                              |
|   YEAR    SERVICEABILITY     |
|                              |
|                              |
|                              |
|                              |
|                              |
|                              |
|                              |
 ------------------------------
```

```
 --------------------------------------------------------------------------
|                                                                          |
|                                   LAYERS                                 |
|    TYPE      DESCRIPTION      ACTIVITY      DATE(M/Y)      DEPTH(IN.)    |
|                                                                          |
|                                                                          |
|                                                                          |
|                                                                          |
|                                                                          |
|                                                                          |
 --------------------------------------------------------------------------

 --------------------------------------------------------------------------
|                                                                          |
|                           DISTRESS DENSITIES                             |
| DISTRESS    (SQUARE FEET)          LOW           MEDIUM          HIGH    |
|     BLEEDING                       400                                   |
|     BLOCK CRACKING                                                       |
|     CORRUGATION                                                          |
|     DEPRESSION                                                           |
|     RUTTING                                                              |
|     SHOVING                                                              |
|     SLIPPAGE CRACKING                                                    |
|                                                                          |
|             (LINEAR FEET)          LOW           MEDIUM          HIGH    |
|     SWELLING                                                             |
|     EDGE CRACKING                  100                                   |
|     LANE/SHOULDER                                                        |
|       DROPOFF                                                            |
|                                                                          |
 --------------------------------------------------------------------------
```

```
 ------------------------------
|                              |
|  FATIGUE CRACKING (% AREA)   |
|                              |
| PANEL   L     M    H    TOT  |
|   1          11.7 16.7  28.4 |
|   2           6.7 11.7  18.4 |
|   3           8.3        8.3 |
|   4           6.7  5.0  11.7 |
|   5           5.0  1.7   6.7 |
|   6          10.0  6.7  16.7 |
|   7          10.0       10.0 |
|   8               26.7  26.7 |
|   9           8.3 36.7  45.0 |
|  10           3.3 41.7  45.0 |
|  11           3.3 48.3  51.6 |
|  12           5.0 48.3  53.3 |
|  13           5.0 36.7  41.7 |
|  14           3.3 40.0  43.3 |
|  15           5.0 36.7  41.7 |
|  16           5.0 36.7  41.7 |
|  17          10.0 36.7  46.7 |
|  18           6.7 36.7  43.4 |
|  19           6.7 36.7  43.4 |
|  20          13.3 31.7  45.0 |
|                              |
|  % OF SECTION CRACKED  33.4  |
|                              |
 ------------------------------
```

Figure A-7. Pavement characterization data.

ENVIRONMENT

PRECIPITATION (IN.) : 48

FREEZING INDEX (BASE 32F) : 25

WET FREEZE-THAW CYCLES : 65

TOTAL FREEZE-THAW CYCLES :

TRAFFIC (CUMULATIVE)

FROM (M/Y)	TO (M/Y)	VEHICLES
FROM (M/Y)	TO (M/Y)	ESAL
1938	1983	1040257
YEAR	ADT	% TRUCKS
1963	1100	
1973	1650	
1983	1850	

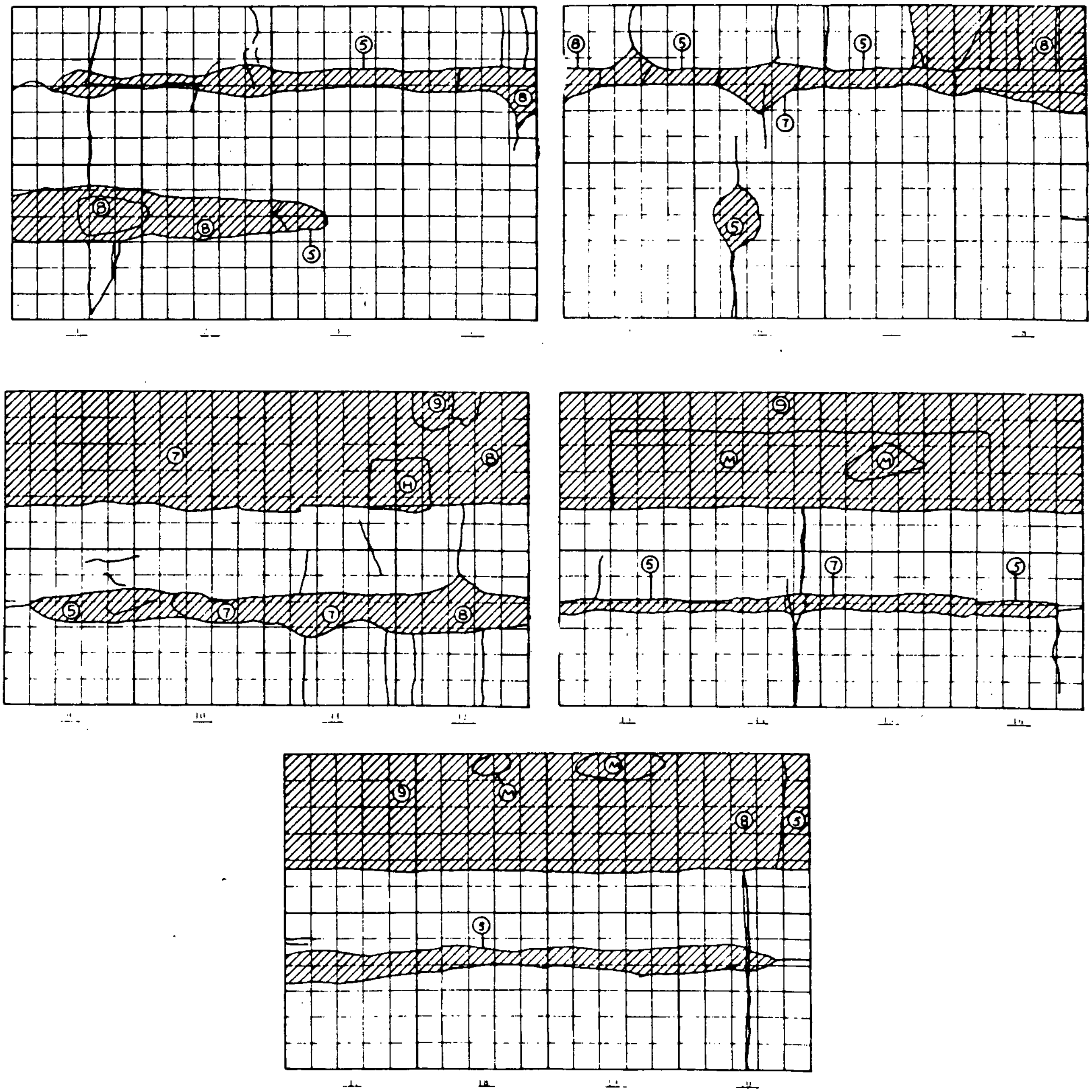


Figure A-7. Continued

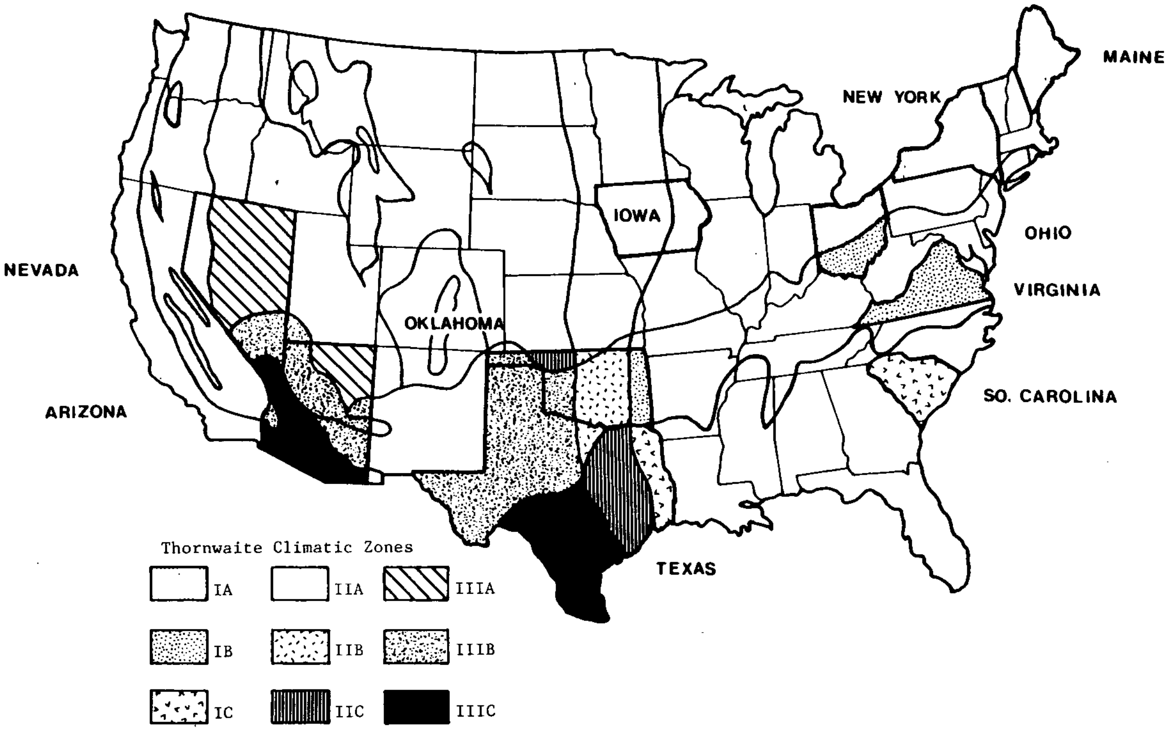


Figure A-8. Map showing States where test locations were established.

APPENDIX B

COMPUTER PROGRAM DESCRIPTION

Project 14-6 produced two computer programs.* One is AGENCY, which can be used to calculate costs for highway agencies for different maintenance strategies on different classes of highways. The output of this program can be used as input for IMPACT, which is a program to compute the costs to road users and nonusers of different maintenance strategies.

The computer program AGENCY calculates the direct maintenance and repair costs incurred by organizations responsible for maintaining roads. These costs result from pavement deterioration due to traffic, environmental forces, the pavement's structure and type, and maintenance timing. Figure B-1 is a generalized chart of the flow of the AGENCY subroutines for rigid and for flexible pavements.

To determine maintenance and repair costs, AGENCY predicts pavement distress, compares the distress with condition thresholds that define maintenance levels, alters the distress condition to reflect performed maintenance, adjusts the distress predictions to reflect the effect of maintenance on future pavement performance, and computes the costs and days of each maintenance activity.

AGENCY analyzes rigid pavements and flexible pavements. AGENCY is designed to be run alone and generate maintenance and repair costs for different maintenance service levels. The option exists to automatically interface AGENCY output on serviceability and days of road occupancy with the program IMPACT.

---

* Disks containing both the AGENCY and IMPACT programs and further program documentation for each program are available on a loan basis from the Director, Cooperative Research Programs. Request the available disks by name and the documentation by Volume 2 (User's Guide) of the Draft Final Report, NCHRP Project 14-6, "Evaluating Deferred Maintenance Strategies."

AGENCY

AGENCY is composed of two subroutines called AGENCYR and AGENCYF. Each requires inputs of as-constructed data, environmental information, traffic, present conditions, maintenance levels, and financial data.

Variables are entered from an input file. The number of variables, although not excessive, is large enough to demonstrate the need for the program AGENCY. The individual calculations are simple but, taken in concert, the analysis quickly becomes quite complex.

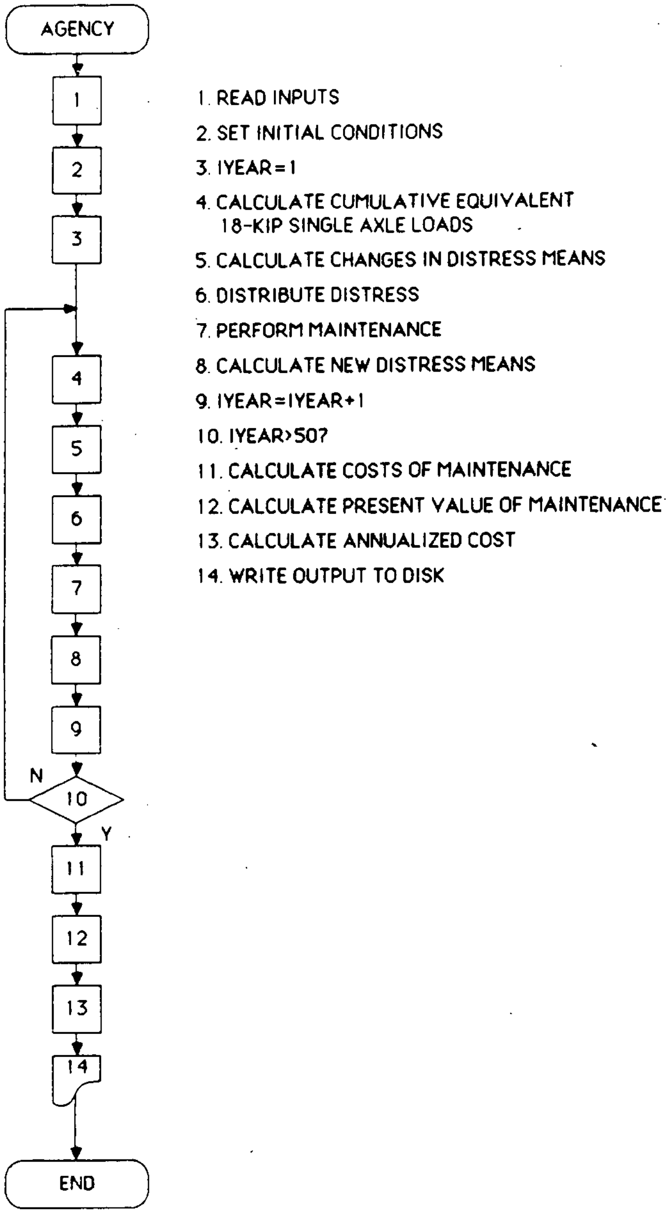


Figure B-1. Generalized flow chart.

Subroutine AGENCYR

Subroutine AGENCYR is a methodology to analyze rigid pavements. The subroutine employs damage equations for jointed reinforced concrete pavements (JRCP) and jointed plain concrete pavements (JPCP). Because there is only a small percentage of continuously reinforced concrete pavements (CRCP) in the Federal Aid System, a lack of CRCP distress models, and scant data on maintenance effects on distress progression, no CRCP methodology was developed.

Models

With the exception of models for patching and for joint and crack sealant failure, AGENCY draws models from the Cost Allocation study (*B-1*).

A major drawback to the Cost Allocation models is that they are not linked to each other. Reduction in PSI is not linked to faulting, which is not linked to pumping. A danger with these models in an analysis that allows maintenance to change the level of some distress without changing the level of another is that unrealistic situations can occur. For example, if a pavement that is badly faulted is ground, PSI will not change because faulting is not an input to the model that predicts reduction in PSI.

A second problem with the Cost Allocation models is that the output is deterministic. Maintenance workload is a function of the distribution of a distress, and a prediction of a mean fault of 0.15 in. (3.81 mm) is of little use to maintenance personnel who grind all faults greater than 0.20 in. (5.08 mm). Predicting maintenance workload requires a distribution for each distress. Some distributions are easily measured, while others must be inferred. Faulting is a distribution that is easily measured, but distributions of voids are not so easily measured.

For these reasons, the Cost Allocation models have all been modified to some degree.

Joint and Crack Sealant. The model for joint and crack sealant failure is based on work done by Riggins, et al. (*B-2*) regarding pavement distress and serviceability.

The model for sealant life is:

$$\text{Percent Intact} = e^{AGE \, *Z}$$

$$Z = -0.7/LIFE^3$$

where: AGE = sealant age, years; and LIFE = years until 50 percent of seals are failed.

This model is conceptually attractive, the "S" shape of the curve in Figure B-2 shows few failures early in the life of the sealant, accelerating rapidly near the expected mean life, and decelerating thereafter. In addition, inputs for this model are simple, requiring only expected mean life and age.

As stated earlier, most of the models used in this subroutine are adapted from the Cost Allocation study. The general form of Cost Allocation models is:

$$g = (ESAL/RHO)^{BETA}$$

where: g = damage in terms of PSI; and ESAL = cumulative equivalent 18-kip (80 kN) single-axle loads, millions. Values of RHO and BETA are specific to each type of distress, and are calculated using the following formulas.

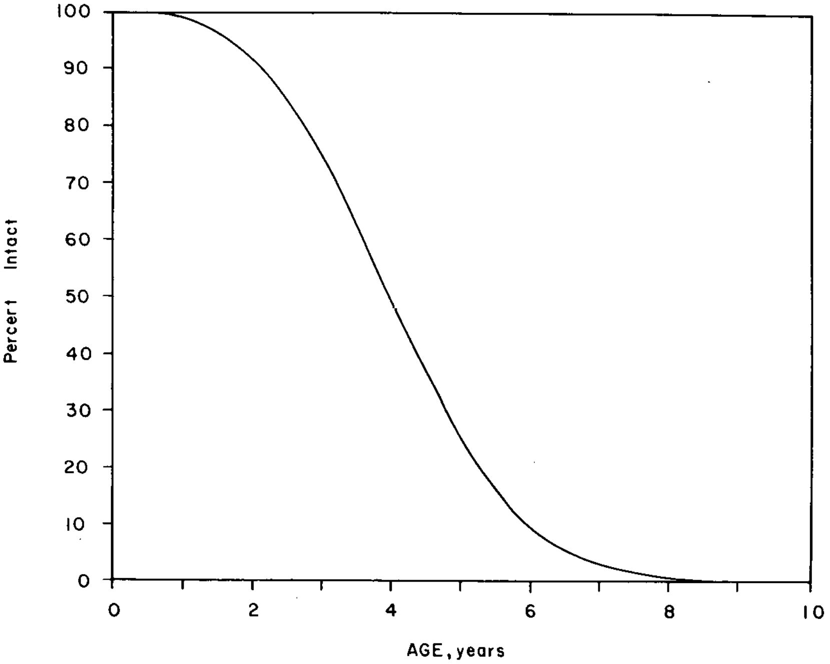


Figure B-2. Graph of sealant life model output.

PSI Reduction. The Cost Allocation model for predicting loss in PSI is:

JRCP

$$\begin{aligned} \ln\text{RHO} &= 0.4593*\text{THICK} - 0.01167*\text{IMOIST} + 0.6758 \\ &\quad *\text{BASETYP} - 1.709 \\ \text{BETA} &= 7.656/\text{SPACING} + 0.04152*\text{BASETHI} \\ &\quad + 0.43516 \end{aligned}$$

JPCP

$$\begin{aligned} \ln\text{RHO} &= 1.333*\text{SOILTYP} - 0.009024*\text{FRINDEX} \\ &\quad + \text{BASETYP}*(1.156*\text{THICK} - 6.966) \\ &\quad + \text{JLTS}*(0.6556*\text{THICK} + 1.763) \\ &\quad + 0.803 \\ \text{BETA} &= 0.0006076*\text{FRINDEX} + \text{BASETYP} \\ &\quad *(-0.0683 - 0.01435*\text{THICK}) \\ &\quad + \text{JLTS}*(0.7107 - 0.09997*\text{THICK}) \\ &\quad + 0.544 \end{aligned}$$

where: THICK = slab thickness, inches; IMOIST = Thornthwaite moisture index; BASETYP = 0 nonstabilized subbase/1 stabilized subbase; SPACING = slab length, feet; BASETHI = base thickness, inches; SOILTYP = 0 fine grained/1 coarse grained; FRINDEX = freezing index (32°F, CE method); and JLTS = joint load transfer system, 0 no dowels/1 dowels.

Figure B-3 shows a plot of PSI versus cumulative 18-kip (80 kN) equivalent single-axle loads for a 10-in JRCP pavement with environmental conditions like those of the Illinois Tollway. Beginning equivalent 18-kip (80 kN) axles are 220,000 with a growth rate of 10 percent. The life of the pavement using 2.3 as the terminal PSI is almost 23 years. Sections of the Illinois Tollway with this level of traffic and a high level of maintenance lasted on the order of 14 years before rehabilitation. Therefore, the output of the PSI model is unreasonably high, and is due to omitting environmental effects.

AGENCYR uses the reduction in PSI for the period given starting and ending cumulative equivalent 18-kip (80 kN) single axles predicted by the Cost Allocation model. This change is then multiplied by a factor that depends on two parameters, the user's impressions about how intact seals versus failed seals affect reduction in PSI, and on condition of seals on the roadway in question. This factor has a value greater than one for failed seals, and less than one for intact seals. Derivation of the factor is discussed in the section entitled Program Structure. The actual PSI for the previous period is reduced by this factored, predicted reduction.

PSI is further reduced by an environmental factor based on Thornthwaite moisture index and freezing index. This factor has as endpoints "wet-freeze" and "dry-no freeze" environments, with the additional environmental effect for "dry-no freeze" environments equal to zero.

Two further reductions of PSI are an attempt to tie Cost Allocation models together. PSI is changed as a function of the change in required patching that has not been patched. A reduction in this residual patching causes PSI to increase, while an increase reduces PSI. This factor is based on the observation that each potential patch is a cracked area, for which the reduction in PSI is due to the resulting fault. This fault will not be predicted by the Cost Allocation model for faulting and must be accounted for in some fashion. The subroutine used to predict change in PSI for an associated change in faulting, gave a rough approximation of a reduction in PSI of 0.002 for each additional fault. Therefore, for each increase in residual patching of a standard size patch, PSI is reduced by 0.002.

The final modification to PSI is also a result of faulting. The original change in PSI is related to an amount of faulting pre-

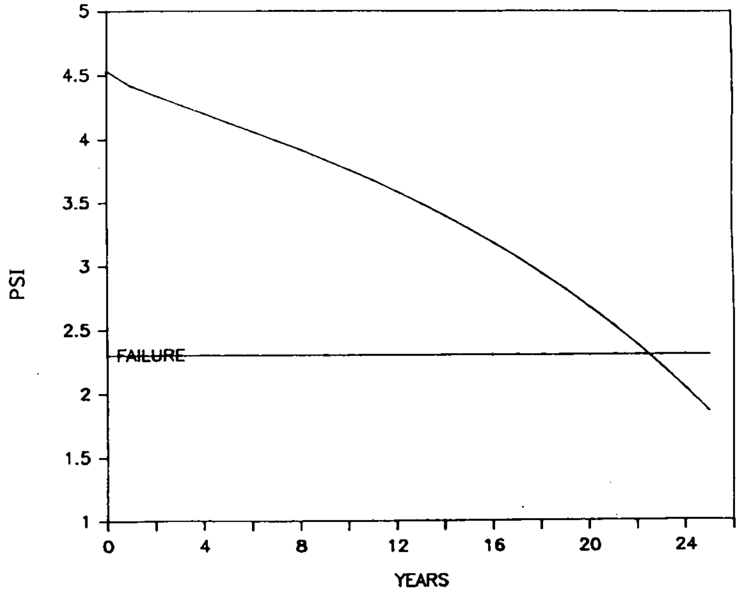


Figure B-3. Predicted life of Illinois Tollway using cost allocation model.

dicted by the Cost Allocation models, but the actual amount of faulting in the analysis may be very different, especially due to grinding. For this reason the difference between predicted faulting and actual faulting is subtracted from PSI.

The final form of the PSI model is:

PSI = PSI last period − Factored predicted change in PSI − Environmental effect − Effect of change in residual patching − Effect of difference between predicted and actual faulting

Pumping. Cost Allocation models for pumping are:

JRCP

$$\ln RHO = 1.39*DRAINTY + 4.13$$

$$BETA = 0.772*(THICK - 2.3)^{1.61}/SUMPREC + 0.0157*JLTS*THICK + 0.104*BASETYP + 0.17*DRAINTY + 0.137*SOILTYP - 0.247$$

JPCP

$$\ln RHO = 1.028*BASETYP + 0.0004966*THICK - 0.01248*FRINDEX + 1.667*CBR + 5.476$$

$$BETA = -0.01363*IMOIST + 0.02527*THICK + 0.423$$

where: DRAINTY = 0 no underdrains/1 underdrains exist; THICK = slab thickness, inches; SUMPREC = average annual precipitation, cm; JLTS = joint load transfer system, 0 no dowels/1 dowels; BASETYP = 0 nonstabilized subbase/1 stabilized subbase; SOILTYP = 0 granular foundation soil/1 coarse foundation soil; FRINDEX = freezing index (32°F, CE method); CBR = California Bearing Ratio of foundation soil; and IMOIST = Thornthwaite moisture index.

Output from these models is a number from 0–3. This corresponds to a scale of 0 no pumping to 3 severe pumping.

At first glance, pumping output is on an ordinal scale, and attempts to use this output as a value on a ratio scale would be unjustified in a statistical sense because the difference between classifications is not defined, and the difference between no pumping and slight pumping may not be the same as the difference between slight and moderate or moderate and severe pumping. Study of the Cost Allocation report indicates that the authors of that report intended the output of these models to be continuous, and more than just an ordering of outputs into categories. With this observation, data were used from the AASHO Road Test to calibrate curves produced with Cost Allocation models.

Using as-constructed and environmental inputs corresponding to the AASHO Road Test, curves of pumping vs cumulative equivalent 18-kip (80 kN) single axles were generated, and calibrated by eye to data from the road test (*B-3*). After each rain during the road test, the volume of material ejected from beneath slabs was estimated, recorded, and removed. These data were recorded as a pumping index of cubic inches per inch of slab length. Output from the calibrated Cost Allocation curves is in units of cubic feet per foot of slab length. These units along with slab length input by the user allows us to predict the mean void per slab produced by pumping. The calibrated Cost Allocation pumping equations are:

JRCP

$$Pumping = (g/THICK^3) * \ln(ESAL)^{2.3}$$

JPCP

$$Pumping = (g/THICK^4) * \ln(ESAL)^3$$

where: ESAL = cumulative 18-kip equivalent single axles; and THICK = slab thickness, inches.

As with PSI, pumping for each period is determined using the change in pumping predicted by the Cost Allocation models for ESAL at the end of the present period and ESAL at the end of last period as the starting point for calculations. This change is distributed to each slab according to a distribution provided by the user. The pumping change for each slab is then modified by a multiplier for sealing that is much the same as that for PSI. In addition, there is a modifier for undersealing that is based on the effectiveness of undersealing in reducing progress of pumping and on the age of the undersealing. If the slab has never been undersealed, or if the underseal is older than the effective life that was input by the user, the multiplier is one, and there is no effect. Undersealant younger than the effective life will have reduced effectiveness in proportion to its age. The utility of undersealing is decreased from that effectiveness input by the user at age zero to none at the effective life.

As was discussed earlier, a distribution of voids cannot be readily measured. For this reason a distribution like that for faulting was used. Since pumping and faulting are due to the same causes, and because there are no recorded distributions for void size, this was viewed as an adequate expedient, but further study of voids under pavements is needed.

Faulting. Cost Allocation models for JRCP AND JPCP predict mean fault in inches, and are of the following form:

JRCP

$$\begin{aligned}\mathrm{lnRHO} &= 1.5754*\mathrm{THICK} - 0.09256*\mathrm{IMOIST} - 8.173\\ \mathrm{BETA} &= -0.0972/\mathrm{CBR} + 0.0061*\mathrm{THICK}*\mathrm{DOWDIA}\\ &\quad -3.175*10^{-6}*\mathrm{FRINDEX}\\ &\quad *\mathrm{SUMPREC} + 0.2935\end{aligned}$$

JPCP

$$\begin{aligned}\mathrm{lnRHO} &= \mathrm{JLTS}*(-0.1444*\mathrm{THICK}^2\\ &\quad + 3.48*\mathrm{THICK} - 14.68)\\ &\quad + 3.2*\mathrm{BASETYP} - 0.009*\mathrm{IMOIST}\\ &\quad - 0.005332*\mathrm{FRINDEX} + 1.8534\\ \mathrm{BETA} &= 0.0021*\mathrm{CBR} + 0.0052*\mathrm{SOILTYP}\\ &\quad - 0.001196*\mathrm{CSTE} + 0.63*\mathrm{JLTS} + 0.292\end{aligned}$$

where: THICK = slab thickness, inches; IMOIST = Thornthwaite moisture index; CBR = California Bearing Ratio of foundation soil; DOWDIA = dowel bar diameter, inches; FRINDEX = freezing index (32°F, CE method); SUMPREC = average annual precipitation, cm; JLTS = Joint Load Transfer system, 0 no dowels/1 dowels; BASETYP = 0 nonstabilized subbase/1 stabilized subbase; SOILTYP = 0 granular foundation soil /1 coarse foundation soil; and CSTE = concentration of summer thermal efficiency.

These models require no modification other than to multiply the distributed change by the sealant and undersealing modifiers. This mean change is then distributed to slabs in the same way that pumping was distributed. Sealant and undersealing modifiers are of the same form as those for pumping.

Cracking. Cost Allocation models to predict cracking are:

JRCP

$$\begin{aligned}\mathrm{lnRHO} &= 79.51/\mathrm{SUMPREC} - 0.5949*\mathrm{THICK}\\ &\quad + 0.053188*\mathrm{THICK}^2 + 0.7*\mathrm{DRAINTY}\\ &\quad - 0.0011546*\mathrm{FRINDEX} + 0.550745\\ &\quad *\mathrm{BASETYP} + 2.805\\ \mathrm{BETA} &= -0.003513*\mathrm{IMOIST} + 1.324\end{aligned}$$

JPCP

$$\begin{aligned}\mathrm{lnRHO} &= \mathrm{JLTS}*(5.722 + 0.0435*(\mathrm{THICK} - 7)^3\\ &\quad - 1.7*\mathrm{PUMPING}) + \mathrm{BASETYP}\\ &\quad *(0.535*\mathrm{THICK}^2 - 0.2745*\mathrm{THICK})\\ &\quad + 1.698*\mathrm{SOILTYP}\\ &\quad - 0.105\mathrm{TDIF} + 2.386\\ \mathrm{BETA} &= 0.16*\mathrm{BASETYP} + 1.51\end{aligned}$$

where: SUMPREC = average annual precipitation, cm; THICK = slab thickness, inches; DRAINTY = 0 no underdrains/1 underdrains; FRINDEX = freezing index (32°F, CE method); BASETYP = 0 nonstabilized subbase/1 stabilized subbase; IMOIST = Thornthwaite moisture index; JLTS = Joint Load Transfer system, 0 no dowels/1 dowels; PUMPING = severity of pumping—0 none, 1 low, 2 medium, 3 high; SOILTYP = 0 granular foundation soil/1 coarse foundation soil; and TDIF = average monthly temperature range, °C.

Each period, the increase in cracking is distributed in the same way that pumping and faulting are distributed. The changes for each slab are modified by multipliers, depending on the state of sealant and undersealing for the slab. These multipliers are of the same form as those for pumping and faulting and are functions of values provided by the program user of the effects of sealing and undersealing on cracking.

Patching. There was no model for patching in the Cost Allocation report. As a result, a model was adapted from EAROMAR (*B-4*) and calibrated with data from the Illinois Tollway (*B-5*). This model is:

$$\begin{aligned}\mathrm{PATCHING} &= \mathrm{F}/(1.0 + e^{(1.0-\mathrm{AGE}-1.)/1.25)}\\ \mathrm{F} &= e^{(2.0+1.75*\mathrm{PSINIT}-\mathrm{PSI10})}\end{aligned}$$

where: PATCHING = potential square yards of patching per period per lane mile; AGE = pavement age, years; PSINIT = as-constructed PSI; and PSI10 = PSI predicted by Cost Allocation at AGE = 10.

PSI predicted by Cost Allocation for the tenth year of the analysis is used as the inflection point for an "S" shaped curve predicting patching. The model predicts square yards of patching for each period. This is a measure of potential patching and may not all be included in the patching workload for the analysis, depending on the level of service provided by the maintenance agency. For example, under a high level of service, each crack might be viewed as an opportunity for patching, and all of the predicted patching would be added to the maintenance workload for the period. Under a lower level of service, only a smaller percentage of the predicted patching would be considered a patching opportunity. This lesser percentage would be added to the workload for the period, while all of the potential patching would be used in calculations for reducing PSI as discussed in the paragraph on PSI earlier in this section.

A user-specified percentage of the patching workload is designated as temporary patching. This is patching that is done as quickly as possible, usually under adverse circumstances in an effort to disrupt traffic as little as possible, with the knowledge that these patches do not have long lives. The life of this type of patch is provided as an input by the user, and once the temporary patch reaches this age, it reenters the workload for that period.

Permanent patching is distributed in a number of full lane width patches. A standard patch length of 8 ft (2.44 m) was chosen as a result of information from a report on Experimental Rehabilitation of Jointed PCC Pavement (*B-6*). The area for each patch is multiplied by a factor for sealing and undersealing in the same way that these factors were used for other types of distress. Patches are distributed to slabs starting at the end of the array that generally gets the largest changes in distress. The user can limit the number of patches that each slab can receive over the analysis in order to keep from always putting patches into the same slabs.

Inputs

The as-constructed inputs to RIGID depend on whether the pavement is JRCP or JPCP.

Inputs for JRCP include:

- Slab thickness, in.
- CBR
- Subbase thickness, in.
- Underdrains (0-none/1-present)
- Subbase type (0-nonstabilized/1-stabilized)
- Dowel bar diameter, in.
- Slab length, ft
- As constructed PSI
- Lane width, ft

Inputs for JPCP include:

- Slab thickness, in.
- CBR
- Foundation soil type (0-granular/1-coarse)
- Underdrains (0-none/1-present)
- Subbase type (0-nonstabilized/1-present)
- Slab length, ft
- As constructed PSI
- Lane width, ft

Environmental inputs include:

- Average annual precipitation, cm
- Freezing index (32°F, CE method)
- Thornthwaite moisture index

In addition to the above environmental inputs. JPCP requires average monthly temperature range in degrees and concentration of summer thermal efficiency. Concentration of summer thermal efficiency, the percent of yearly evapotranspiration that occurs during the summer months, is more extensively defined by Thornthwaite (*B-7*).

Plain and reinforced concrete pavements have common inputs for present condition including:

- Initial PSI
- Pumping (0 none/1 slight/2 moderate/2 severe)
- Mean fault, in.
- Cracking, ft/mi
- Patching, sq yd/mi
- Sealant age, years
- Starting year 18-kip equivalent single axles (ESAL)
- ESAL growth, percent

Both pavement types have common maintenance threshold inputs. These include a thereshold void size, used to trigger undersealing. Voids larger than the threshold void are counted. When this count exceeds the number specified by the program user, undersealing is triggered. In the same manner, faults greater than a specified threshold are counted to trigger grinding. Joint and crack sealing can be triggered in two ways, percent of joint and crack seals failed, or time.

Included in the maintenance level inputs are variable flags to specify continuous versus spot grinding, and partial or total seal replacement. If spot grinding is specified, only those faults greater than the threshold fault are ground, as opposed to grinding all of the faults. The other flag controls sealing. The program user can specify that during sealing operations, all seals or just failed seals be replaced.

The program user also specifies treatment effectiveness. Sealing, undersealing, and patching life are all inputs. Other inputs are the effectiveness of sealing and undersealing in reducing progressions of other distresses.

Treatment production rate is an input used to determine the number of days of pavement occupancy annually. Production rates are specified in units of accomplishment per day, i.e., linear feet of joint and crack sealing, cubic feet of undersealing, square yards of grinding, square yards of PCC and bituminous patching, and square yards of resurfacing. Daily production rates are based on 6.5 hours of production work daily.

Other inputs include resource constraints by type of maintenance and a resource growth rate. Users can constrain maintenance both by thresholds and by limiting resources. This allows the economic impacts of increasing or decreasing resources to be examined.

Another set in inputs address economic facets of the analysis. These include:

- A discount rate or opportunity costs of money.
- Unit costs for each maintenance treatment.
- Optional inflation rates to handle anticipated inflation disparities for different materials.

Program Structure

AGENCYR simulates the performance of 50 slabs or joints, depending on the distress.

AGENCY reads an input file containing the variables discussed in the previous section. The subroutine then initializes arrays and calculates damage values for initial conditions. The program then enters the main loop in the analysis. Joint and crack seals are failed depending on the effectiveness of the sealant material and its age. Multiplying factors are calculated and used to modifying the evaluation of distress. These factors depend on sealant condition, i.e., sealant is intact or failed. Failed seals generate a modifying factor smaller than one. The modifying factor size depends on user inputs of intact seal effectiveness in reducing distress progression and are symmetrical about 1.0. If the user inputs 50 percent, this means that intact seals reduce pumping 50 percent of that with failed seals. A modifying factor is determined for each joint and is computed as follows:

$$\text{Intact seal factor} = 1 - ((100 - \text{effect})/(100 + \text{effect}))$$
$$\text{Failed seal factor} = 1 + ((100 - \text{effect})/(100 + \text{effect}))$$

giving:

$$\text{Failed Seal} = 1.333$$
$$\text{Intact Seal} = 0.667$$

A 1-cu ft void due to pumping becomes 0.667 cu ft (0.019 m^3) or 1.33 cu ft (0.038 m^3), depending on the sealant condition.

This modifying factor is based on the observation that existing damage models reflect field data where there was some level of maintenance, including joint and crack sealing. The level is unknown, but a typical field condition is that 50 percent of seals are failed. This is treated as an average maintenance level and modifiers are developed for this 50 percent failed seals condition. This reference modifier has a value of 1.

One problem addressed in developing the RIGID subroutine was handling maintenance that changes the distress condition. For example, Figure B-4 shows progression of mean fault. If grinding occurs, the mean fault is reduced. The problem is to establish a new progression for faulting. Grinding does not alter the causes of faulting, and one would not expect it to affect the rate at which faulting progresses. The shape of the faulting curve is, therefore, the same after grinding.

On the other hand, undersealing does change the rate at which pumping occurs. Undersealing reduces free water beneath the slab, reduces slab deflection, and may be more erosion resistant than the original base material. Figure B-5 illustrates these relationships. Void size is reduced and pumping progresses not at the original rate, but at some reduced rate.

The extent of undersealing in the damage models data base is unknown. A modifier of one for no undersealing will attribute the maximum value to undersealing as a treatment. The value of the undersealing modifying factor is a user input as is its life. The change in distress for the period is multiplied by this input factor. If undersealing reduces pumping 50 percent and has a life of 5 years, successive values of the modifier are: 0.5, 0.6, 0.7, 0.8, 0.9, 1.0.

In this example, pumping for the period is reduced by 50 percent initially and modified less and less until in the sixth period, there is no effect. The formula for this modifier is:

$$\text{Modifying factor} = 1 - (\text{Percent reduction} * (1 - \text{AGE} * (1/\text{life})))$$

when AGE is greater than or equal to the effective life, the modifier is 1.0.

The way in which pavement serviceability (PSI) changes each year depends on both the damage model (PSI) and adjustments made to PSI loss annually due to maintenance treatment effectiveness and residual conditions. The rate of PSI loss is based on the damage model, and altered annually to reflect maintenance service levels. Understanding the process requires that different PSI terms be defined:

PSI_n = damage model PSI for cumulative 18-kip (80 kN) equivalent single axles
$PSI = PSI_{\text{end of period}} - PSI_{\text{start of period}}$
PSI_m = modified PSI due to seals, underseals, grinding, patching

A change in PSI is computed annually. The PSI damage model generates PSI given the cumulative number of 18-kip (80 kN) equivalent single-axle loads. PSI is calculated for the number of cumulative equivalent axles at the beginning of and end of each period. The difference between these values is the unadjusted change in PSI.

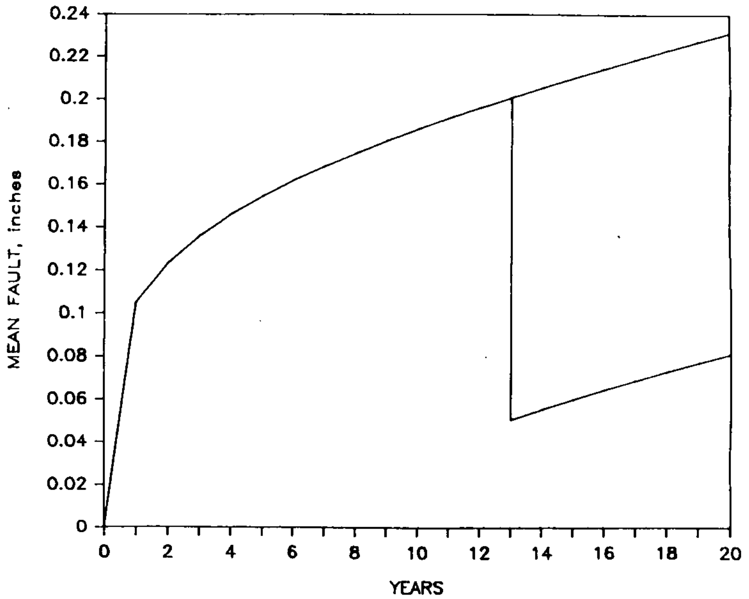


Figure B-4. Faulting progression with and without grindings.

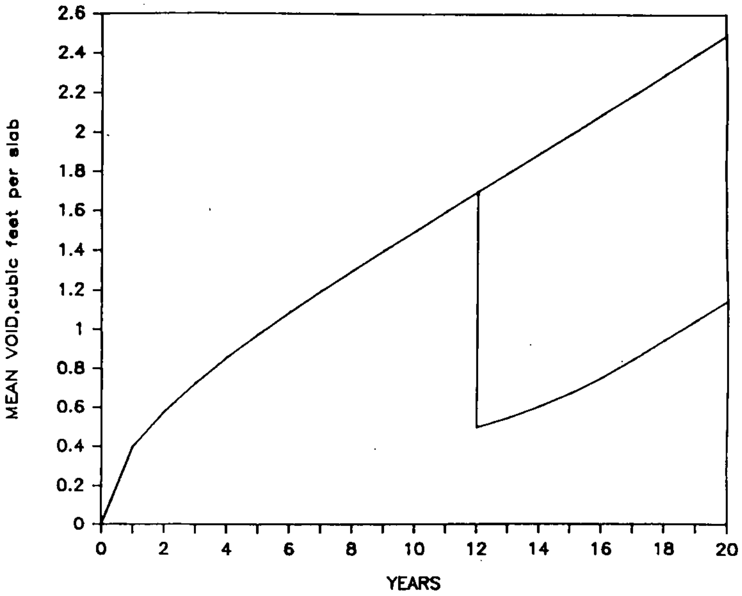


Figure B-5. Void progression with and without undersealing.

An adjustment is made to the PSI loss to reflect the effect of maintenance in extending pavement life. The adjustment involves applying modifying factors to the PSI loss as follows:

$$PSI_m = PSI \times MF_{seals} \times MF_{underseals} \times MF_{grinding} \times MF_{patching}$$

The damage models are also used to compute changes in pumping, faulting, and cracking. Pumping and faulting are calculated for each slab in the simulated roadway according to a distribution selected by the program user. The program provides for four distributions, three of which are supplied with the program, and one which can be created by the program user. The three distributions that are provided are normal, exponential, and uniform. The program uses the distribution to transform a deterministic value of change in distress into a distribution of changes in distress the mean of which is the predicted change in distress.

For the normal distribution, the parameter is the standard deviation of the distribution defined at some reference level of faulting. For example, a pavement might have a faulting standard deviation of 0.1 in. (2.54 mm) when the mean fault is 0.2 in. (5.08 mm). The standard deviation of faulting at the reference level is divided by the reference level of faulting. The factored standard deviation is then multiplied by the predicted change in faulting. This number is then multiplied by one of the standard normal "Z" values read from the distribution input file. The resulting number is the difference between the predicted change in fault and the change in fault to be assigned to a single slab. The difference is multiplied by modifying factors that are a result of maintenance performed on the slab. Finally, the modified change in fault height is added to the fault for the previous period.

Predicting the change in void size is complicated by a lack of data about distributions of void sizes. Although fault height distributions have been collected, distributions of void sizes have not. Maintenance personnel may have a feel for faulting distributions, but it is unlikely that they will have a feel for the distribution of voids under a pavement. Because faulting and void creation are due primarily to the same mechanism, pumping, the factored standard deviation of the faulting distribution was used to distribute changes in voids.

The normal distribution is characterized by a pavement in which most slabs have levels of distress near the mean distress, with a few slabs having relatively very high and relatively very low levels of distress. The standard deviation is the amount a value differs on average from the mean. For this distribution, approximately two-thirds of the values will lie within one standard deviation of the mean value.

The exponential distribution uses the natural logarithm to distribute changes in faulting and void formation and as such requires no further input by the user. The 50 points of the distribution are multiplied by the predicted change in distress and then multiplied by the maintenance modifying factors to calculate the change in distress for each slab. This distribution is characterized by many slabs having almost no distress, while a few slabs have severe distress.

The uniform distribution requires a range at a reference mean fault. For example, a range of 0.1 in. (2.54 mm) at a mean fault of 0.2 in. (5.08 mm) would define a distribution in which faults range evenly from 0.1 to 0.3 in. (2.54 mm — 7.62 mm).

Cracking is distributed by dividing the increase in cracking by the pavement width to determine an increase in transverse cracks. When these cracks are distributed to slabs, their lengths are modified by maintenance multipliers to reflect maintenance that has been performed on the slab.

A patching requirement is calculated for each period. Patches are distributed to slabs after being modified by sealant condition and undersealing.

Seals are failed as a function of sealant age and the user's input of the time to reach failure of 50 percent of the seals.

The program determines if maintenance is required. If so, maintenance is executed up to the limits of resources available. When undersealing is triggered, each slab with a void larger than the input threshold value is undersealed. The void undersealed is set to zero and the age of the undersealant is set to zero.

Grinding, once triggered, depends on whether the user has specified spot or continuous grinding. If continuous, all joints are ground. Spot grinding addresses only those faults larger than the input threshold. In either case, after joints are grouped, they are set to zero. The grinding workload per joint specified by the user is added to grinding performed in the current period.

PSI is improved when the pavement is ground. The effect of faulting in reducing pavement serviceability is based on a pavement roughness calibration procedure that was developed by Taxas Research and Development Foundation (TRDF) as part of the Brazil Cost Study (*B-8*). The procedure was further refined and validated by Querioz, et al. (*B-9*). A rod and level profile is converted into a roughness statistic termed RSMVA that correlates extremely well with response type road roughness measuring equipment. The procedure was used to generate a roughness statistic on pavements with a PSI ranging from 4.0 to 2.0. By using a microcomputer program, faults were superimposed on pavements having a 2.0 and 4.0 PSI and no faults, and initial PSI and slab length were related to pavement serviceability. The plots of the relationships are shown in Figure B-6. These relationships are defined in a routine called FLTSIM that is included in the subroutine, AGENCYR. This routine passes faults before and after grinding and PSI before grinding. The routine generates a random signal that simulates the profile of the pavement. The routine varies the amplitude of the random signal until the signal with the faults superimposed gives the pregrinding PSI. PSI is calculated from the root mean square vertical acceleration (RMSVA) statistic using an algorithm developed by Queriroz (*B-9*). The before-grinding faults are then replaced with the faults after grinding, and PSI after grinding is calculated using the RMSVA.

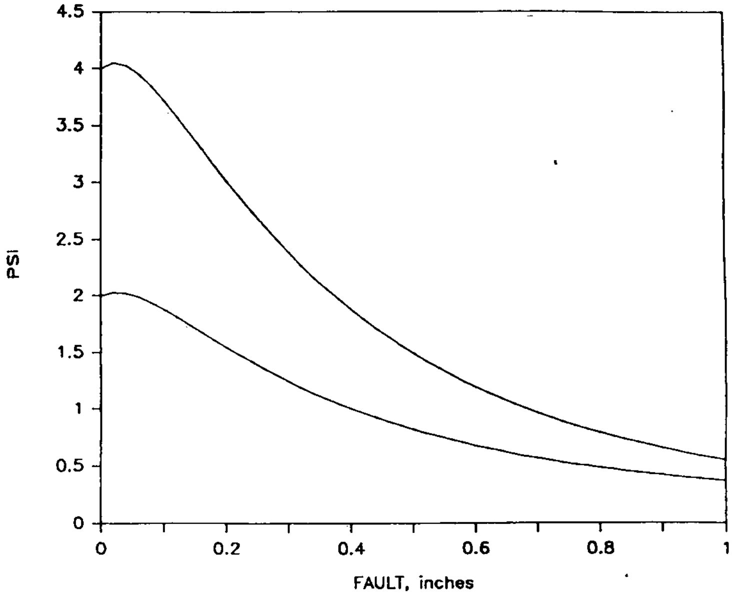


Figure B-6. PSIs of pavements with initial PSIs of 2.0 and 2.0 with superimposed faults.

Patching is divided into temporary and permanent patching. Patching is performed up to the limits of resources available. When permanent patches are made, cracking is reduced in proportion to the area patched.

If sealing is triggered by either time or percentage of seals failed, sealing is performed up to the limits of sealing resources available. The age of a replaced seal is set to zero, and the number of seals replaced is recorded.

Levels of distress after maintenance are calculated and used to determine modifying factors and distress at the start of the next period.

If the PSI is less than the terminal PSI set by the user, the program leaves the main loop. Distress remaining following maintenance in the last year is corrected by maintenance.

Maintenance costs are determined annually by applying the maintenance activity unit cost to the quantity of maintenance that is executed. Days of maintenance by activity are determined using the input productivity rates. Maintenance costs and days required to resurface the pavement are also calculated. Annual costs are converted to present value and summed by activity. Finally the present value for each activity is annualized for the analysis period.

Subroutine AGENCYF

AGENCYF is used to analyze flexible pavements. The subroutine uses damage models for a number of combinations of surface and base types.

Models

Modeling flexible pavement distresses proved to be more difficult than modeling those of rigid pavements. Cost Allocation models were initially selected for modeling flexible pavements because they were the most recent and because they had been used for the most part for rigid predictions. Problems quickly developed with outputs produced by these models.

The preliminary step in an attempt to adapt cost allocation models was to examine outputs of the models to determine if they were realistic. This proved to be an exacting task because the final report, as well as earlier draft versions, of the Cost Allocation study contained typographic errors, several of which were significant.

Once these errors were resolved, output of several scenarios of road construction, environment, and loadings were examined. Table B-1 lists inputs for a run for which predictions of PSI are plotted in Figures B-7, B-8, and B-9.

Table B-1. Example inputs for flexible models to verify outputs.

CONSTRUCTION INPUTS	
AC Thickness, inches	6
SN	4.5
Subgrade modulus, psi	10000
AXLE LOADING INPUTS	
ESAL startin year	150000
ESAL growth	5 %
DISTRESS INPUTS	
As-constructed PSI	4.2
Initial PSI	4.2
Initial fatigue cracking, percent	0.0
Initial rutting, inches	0.0
Initial thermal cracking, ft/mile	0.0
THERMAL CRACKING INPUTS	
Penetration Index	3.0
Ring & Ball Softening Point, degrees F	135
% Concentration of the aggregate	87
Solar Radiation, Langleys/day	300
Minimum monthly temperature, degrees F	25

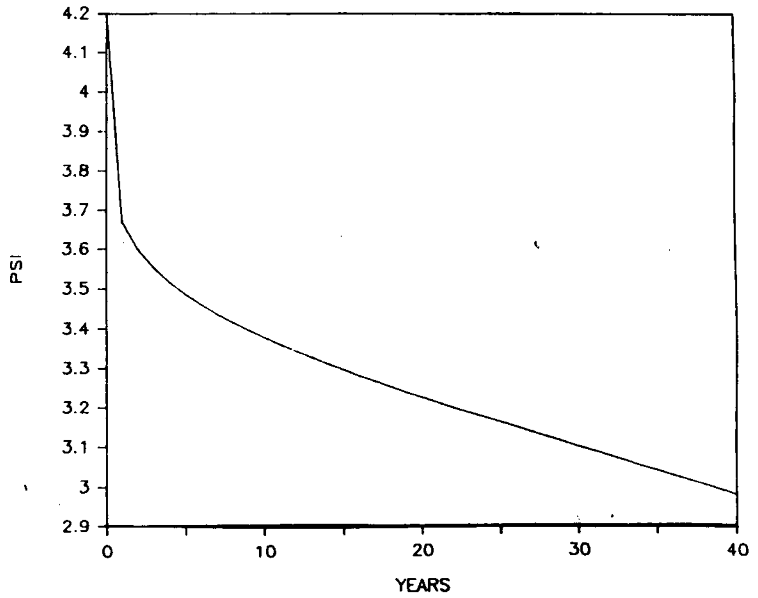


Figure B-7. Output of cost allocation model for reduction of PSI for flexible pavements.

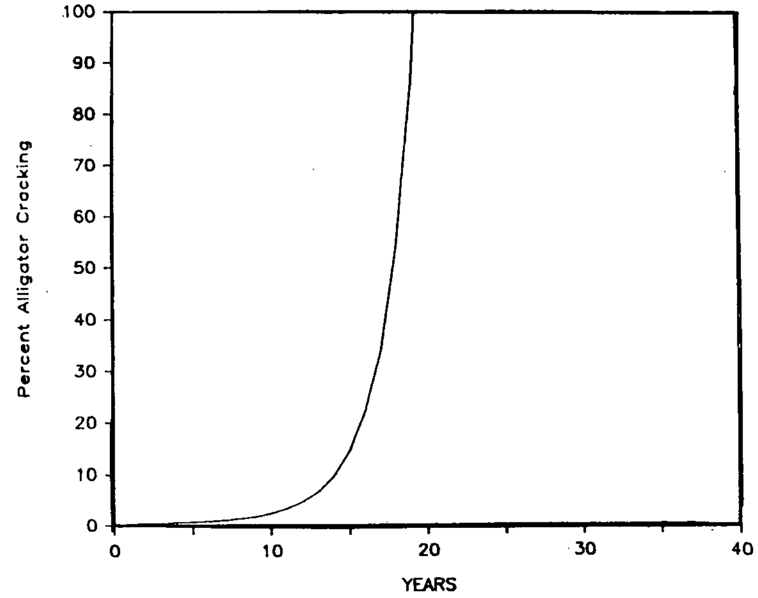


Figure B-8. Output of cost allocation model for fatigue cracking of flexible pavement.

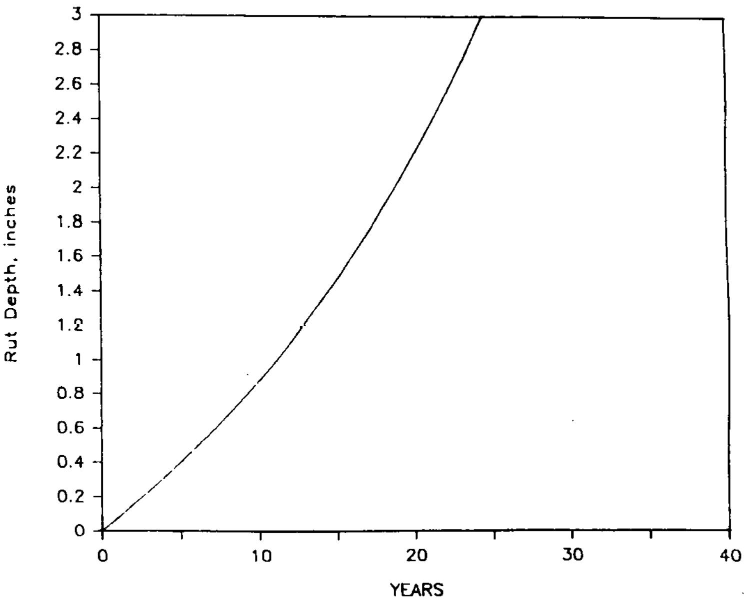


Figure B-9. Output of cost allocation model for rut depth for flexible pavement.

As evidenced by these figures, these models need extensive calibration before they will be useful. Figure B-7 is a plot of PSI for 40 years. The prediction of PSI by itself is suspect because it drops from 4.2 to 3.4 in 9 years, and then drops only 0.4 in the next 31 years. However, taken together with predictions of percent fatigue cracking and rut depth, shown in Figures B-8 and B-9, predictions of PSI are even more unlikely. For example, in year 20 the Cost Allocation equations predict more than 100 percent alligator cracking and rut depth of 2.2 in., and yet PSI is predicted to be 3.2. This is an unlikely combination of distresses, and points to a major problem with all of the Cost Allocation models. For these reasons, distress models from the World Bank's Highway Design Manual were selected to replace models from the Cost Allocation study.

The World Bank's Highway Design Manual (*B-10*) contains models for AASHTO Classes 2 and 4 cracks, ravelling, potholes, mean rut depth, rut depth standard deviation, and roughness. Cracking, divided into categories of "all" and "wide", ravelling, and pothole models are all divided into phases of initiation and progression. Models first predict the time of initiation of each distress. The program then determines whether the initiation time has passed. The variables used to predict onset of distress are: TYCRA, the time in years to onset of all cracks; TYCRW, the time in years to onset of wide cracking; TYRAV, the time in years to onset of ravelling; and TMIN, the time to onset of pothole development. Table B-2 lists equations used to predict initiation of all cracks, TYCRA, for all surface types, where: CRT = the cracking retardation time due to maintenance, years; CQ = construction quality of surface (1 construction faults/0 no construction faults); YE4 = the number of equivalent standard axle loads for the year; SNC = modified structural number; HSE = thickness of the surfacing layers; CMOD = resilient modulus of soil cement (cemented base); DEF = mean Benkelman beam deflection under 18-kip (80 kN) load in both wheelpaths; KA = a variable for indicating the presence of all cracking in the old surface layers; KW = a variable for indicating the presence of wide cracking in the old surface layers; HSNEW = thickness of the most recent surface layer; and KCI = calibration constant for cracking initiation.

Table B-3 lists equations used to predict the onset wide cracking, TYCRW,
where: TYCRA = time to initiation of all cracks, years.

Table B-4 lists equations to predict initiation of ravelling, TYRAV, where: YAX = the total number of axles of all types for the analysis year; RRF = ravelling retardation factor determined by maintenance; and KVI = calibration constant for ravelling initiation.

Pothole initiation is calculated by:

$$\begin{aligned} \text{TMIN} &= \max(2 + 0.04*(\text{HSNEW} + \text{HSOLD}) \\ &\quad - 0.5*\text{YAX},2) \text{ if the base} \\ &\quad \text{is noncemented} \\ \text{TMIN} &= \max(6 - \text{YAX},2) \\ &\quad \text{if the base is cemented} \end{aligned}$$

where: HSOLD = total thickness of previous underlying surface layers; and MAX (6 − YAX,2) means use 6 − YAX or 2 whichever is the maximum.

Tables B-5, B-6, and B-7 list equations used in calculating distress progression for all cracking (ACRA), wide cracking (ACRW), and ravelling (ARAV), where: SCRA = min(ACRA,100 − ACRA); MIN (ACRA,180 − ACRA means use ACRA or 100 − ACRA whichever is the minimum; AGE2 = surface layer age; CRP = retardation of cracking progression CRP = 1 − 0.12*CRT; PCRA = percent of area of all cracking before the latest reseal or overlay; SCRW = min(ACRW,100 − ACRW); PCRW = percent of area of wide cracking before the latest reseal or overlay; KCP = calibration constant for cracking progression; and SRAV = min(ARAV,100 − ARAV).

Table B-2. Models for predicting the initiation of all (i.e., narrow) cracking in various pavement types.

Relationship	Pavement Type
A:	Surface treatments, granular base [1] $TYCRA = K_{ci} *(F_c * RELIA + CRT)$
where	$RELIA = 13.2*\exp(-20.7*(1 + CQ)*YE4/SNC^2)$
B:	All surfacings, cemented base (without stress-absorbing membrane) [1] $TYCRA = K_{ci}*(F_c*RELIB + CRT)$
where	$RELIB = 1.12*\exp(.035*HSE + .371*\ln CMOD - .418\ln*DEF - 2.87*YE4*DEF)$
C:	Asphalt concrete, granular base [1] $TYCRA = K_{ci}*(F_c*RELIC + CRT)$
where	$RELIC = 4.21*\exp(0.14*SNC - 17.1*YE4/SNC^2)$
D:	Slurry seal on surface treatment [2] $TYCRA = K_{ci}*(F_c*((0.05*KW + 0.4*KA*(1 - KW))*HSE + (1-KA)*(1 - KW)*RELIA)) + CRT$
E:	Reseal on surface treatment [2] $TYCRA = K_{ci}*(F_c*(2*KW*(1 + 0.01*HSNEW^2) + (1 - KW)*RELIA) + CRT)$
F:	Reseals on asphalt overlay, cemented base (without stress-absorbind membrane) [2] $TYCRA = K_{ci}*(F_c*((0.8*KA + 0.2*KW)*(1 + 0.1*HSE) + (1 - KA)*(1 - KW)*RELIB) + CRT)$
G:	Asphalt overlay on asphalt concrete, granular or bituminous base [2] $TYCRA = K_{ci}*(F_c*((0.05\ KW + 0.4*KA*(1 - KW))* HSE + (1 - KA)*(1 - KW)*RELIC) + CRT)$
H:	Surface treatment reseal on asphalt concrete, granular or bituminous base [2] $TYCRA = K_{ci}*(F_c*(KW*(1 + 0.01*HSNEW^2) + (1 - KW)*(1 + 0.3*HSNEW)*RELIC) + CRT)$

[1] Statistically derived from Brazil-UNDP road deterioration study.
[2] Empirically developed based on Brazil-UNDP study data and judgment.

Table B-3. Models for predicting the initiation of wide cracking in various pavement types.

Relationship	Pavement type and model
A:	Surface treatments, granular base [1] $TYCRW = K_{ci}*\max(2.66 + 0.88*TYCRA, 1.16*TYCRA)$
B:	All surfacings, cemented base (without stress-absorbing membrane) [1] $TYCRW = D_{ci}*(1.46 + 0.98*TYCRA)$
C:	Asphalt concrete, granular base [1] $TYCRW = K_{ci}*(2.46 + 0.93*TYCRA)$
D:	Slurry seal on surface treatment [1] $TYCRW = K_{ci}*(0.70 + 1.65*TYCRA)$
E,H:	All surface treatment reseals, granular [1] or bituminous base [2] $TYCRW = K_{ci}*(1.85 + TYCRA)$
F:	Reseals or asphalt overlay on cemented base (without stress-absorbing membrane [1] $TYCRW = K_{ci}*1.78*TYCRA$
G:	Asphalt overlay on asphalt concrete, granular[1] or bituminous base[2] $TYCRW = K_{ci}*(2.04 + 0.98*TYCRA)$

[1] Statistically derived from Brazil-UNDP road deterioration study.
[2] Empirically developed based on Brazil-UNDP study data and judgment.

Table B-4. Models for predicting the initiation and progression of ravelling of various surfacings.

Relationship Pavement type and model

RAVELLING INITIATION

A: Surface treatments including reseals (ST, RSST, RSAC) [1]
$TYRAV = K_{vi}*(F_r*(10.5*\exp\ (-\ 0.655*CQ - 0.156*YAX))*RRF)$

B: Slurry seal on surface treatment or asphalt concrete (SSST) [1]
$TYRAV = K_{vi}*(F_r*(14.1*\exp\ (-\ 0.655*CQ - 0.156*YAX))*RRF)$

C: Cold-mix surfacing or cold-mix overlay (CMST) [1]
$TYRAV = K_{vi}*(F_r*(8.0*\exp\ (-\ 0.655*CQ - 0.156*YAX))*RRF)$

D: Asphalt concrete and asphalt overlays (AC, OVAC) [2]
$TYRAV = 100$

[1] Statistically derived from Brazil-UNDP road deterioration study.
[2] Default relationship assuming sound specification and construction of asphalt mixture.

Table B-5. Models for predicting all cracking progression in incremental time for various pavement types.

Relationship Pavement type and model

A,D: Surface treatment or slurry seal reseal, granular base [1]

$$DACRA = K_{cp}*5500XSCRA^{0.815}*SNC^{-3.21}*AGE2^{-0.621}*YE4*DTCRA*CRP$$

B: Surface treatment or asphalt concrete, cemented-base (without stress-absorbing membrane) [1]
$DACRA = K_{cp}*RELPB$
where
$RELPB = 2.42*SCRA^{0.591}*CMOD^{0.897}*DEF^{0.636}*YE4*DTCRA*CRP$

C: Asphalt concrete, granular base [1]
$DACRA = K_{cp}*RELPC$
where
$RELPC = 450*SCRA^{0.346}*SNC^{-2.27}*YE4*DTCRA*CRA$

E: Surface treatment reseal on surface treatment, granular base [2]

$$DACRA = \begin{cases} K_{cp}*(24/HSNEW)*DTCRA*CRP & \text{if } ACRA_a \quad PCRA \\ K_{cp}*9.0*DTCRA*CRP & \text{if } ACRA_a \quad PCRA \end{cases}$$

F: Reseals or asphalt overlay, cemented base (without stress-absorbing membrane) [2]

$$DACRA = \begin{cases} K_{cp}*8.0*DTCRA*CRP & \text{if } ACRA_a \quad PCRA \\ K_{cp}*0.3*RELPB & \text{if } ACRA_a \quad PCRA \end{cases}$$

G: Asphalt overlay on asphalt concrete, granular or bituminous base [2]

$$DACRA = K_{cp}*25*SCRA^{.69}*SNC^{-1.6}*YE4*TCRA*CRP$$

H: Surface treatment reseal on asphalt concrete, granular or bituminous base [2]

$$DACRA = \begin{cases} K_{cp}*8.0*DTCRA*CRP & \text{if } ACRA_a \quad PCRA \\ K_{cp}*0.3*RELPC & \text{if } ACRA_a \quad PCRA \end{cases}$$

[1] Statistically derived from Brazil-UNDP road deterioration study.
[2] Empirically developed based on Brazil-UNDP study data and judgment.

Table B-6. Models for predicting wide cracking progression in incremental time for various pavement types.

Relationship	Pavement type and model
A:	Surface treatment, granular base [1] $ACRW_d = K_{cp}*160*SCRW^{0.548}*DEF^{1.48}*YE4*DTCRW$
B:	Surface treatment or asphalt concrete, cemented base (without stress-absorbind membrane) [1] $ACRW_d = K_{cp}*2.87*SCRW^{0.784}*CMOD^{0.558}*YE4*DTCRW$
C:	Asphalt concrete, granular base [1] $ACRW_d = K_{cp}*720*SCRW^{0.281}*SNC^{-2.52}*YE4*DTCRW$
D:	Slurry reseal, non-cemented base [1] $ACRW_d = K_{cp}*2.9*SCRW^{0.8}*TCRW$
E,H:	Surface treatment reseal, non-cemented base [2] $ACRW_d = K_{cp}*(120/HSNEW)*DTCRW$
F:	Asphalt overlay or slurry reseal, cemented base [1] $ACRW_d = K_{cp}*4.5*SCRW^{.65}*DTCRW$
G:	Asphalt overlay, non-cemented base [1] $ACRW_d = K_{cp}*5.2*SCRW^{.69}*DEF^{1.4}*DTCRW$

[1] Statistically derived from Brazil-UNDP road deterioration study.
[2] Empirically developed based on Brazil-UNDP study data and judgment.

Table B-7. Models for predicting the progression of ravelling of various surfacings.

RAVELLING PROGRESSION

All surface treatments, reseals, slurry seal, cold-mix (ST, RSST, RSAC, SSST, CMST) [1]

$ARAV_d = K_{vi}^{-1}*4.42*SRAV^{0.648}*DTRAV/RRF$

Asphalt concrete and asphalt overlays (AC, OVAC) [2]

$ARAV_d = 0$

[1] Statistically derived from Brazil-UNDP road deterioration study.
[2] Default relationship assuming sound specification and construction of asphalt mixture.

Pothole progression is calculated by:

$$DAPOT = \min(DAPOTCR + DAPOTRV + DAPOTP, 10)$$

where:

$$DAPOTCR = KPP*INPOT*\min((4*ACRW/(HSNEW + HSOLD))(1 + CQ)*(YAX/SNC)/(0.8*W), 6) \text{ if } ACRW > 20$$
$$= 0 \text{ otherwise}$$

$$DAPOTRV = KPP*INPOT*\min((0.8*ARAV/(HSNEW + HSOLD))(1 + CQ)*(YAX/SNC)/0.8, 6) \text{ if } ARAV > 30$$
$$= 0 \text{ otherwise}$$

$$DAPOTP = \min(APOT(KBASE*YAX*(AMP + 0.01)), 10)$$

in which: KPP = calibration constant for pothole progression; INPOT = pothole initiation indicator; W = pavement width, feet; APOT = percent of area potholed; AMP = average monthly precipitation, inches; and

$$KBASE = \max(2 - 0.2*(HSNEW + HSOLD), 3) \text{ if granular base}$$
$$= 0.6 \text{ if cement-treated base}$$
$$= 0.3 \text{ if otherwise}$$

Rutting is defined by mean depth and standard deviation. Mean rut depth is calculated using:

$$RDM = KRP*39800*(YE4*1000000)^{E4RM}/(SNC^{0.502}*COMP^{2.30}) \text{ if mean rut depth is zero}$$

$$
\begin{aligned}
&= \mathrm{KRP*((0.166 + E4RM)/AGE3} \\
&\quad + \mathrm{0.0219*AMP*DCRX*} \\
&\quad \mathrm{ln(max(1,AGE3*YE4)))*RDM} \\
&\quad \text{if mean rut depth is greater than zero}
\end{aligned}
$$

where: KRP = calibration constant for rutting progression; E4RM = 0.09 − 0.0009*RH + 0.0384*DEF + 0.00158*AMP*CRX; AGE 3 = construction age; DCRX = change in cracking index for this period, a measure of cracking prior to the last resurfacing; and CRX = cracking index.

Rut standard deviation is defined by:

$$
\begin{aligned}
\mathrm{RDS} &= \mathrm{KRP*4390*RDM^{0.532}*(YE4*100000)^{E4RS}/} \\
&\quad \mathrm{(SNC^{0.422}*COMP^{1.66})} \text{ if mean rut depth is zero} \\
&= \mathrm{KRP*((0.532*DRDM/RDM + (E4RS/AGE3) +} \\
&\quad \mathrm{0.0159*AMP*DCRX*ln(max(1,AGE3*YE4)))*} \\
&\quad \mathrm{RDS)} \\
&\quad \text{if mean rut and standard deviation are both zero}
\end{aligned}
$$

where: DRDM = change in mean rut from last period.

The final distress model is for roughness and is of the form:

$$
\begin{aligned}
\mathrm{DQI} = {} & \mathrm{KGP*(QI^{1.10}/SNCK^{2.76}*YE4 + 1.61*DRDS +} \\
& \mathrm{0.0798*DCRX + 0.8*W*DAPOT)} \\
& \mathrm{+ KGE*0.0207*QI}
\end{aligned}
$$

where: DQI = the change in the quarter car index (QI) this period; KGP = deterioration factor for roughness progression; QI = quarter car index; DRDS = the change in rut depth standard deviation; DAPOT = the change in percent area potholed; W = pavement width, feet; KGE = deterioration factor for the environment-related annual increase in roughness; SNCK = max(1.5,SNC − DSNK) in which:

$$
\begin{aligned}
\mathrm{DSNK} &= 0 \text{ if base not cemented} \\
&= \mathrm{0.000077*(CRX'*HSNEW + ECR*(HSOLD +} \\
&\quad \mathrm{HBASE))} \text{ if base cemented}
\end{aligned}
$$

CRX′ = min(63,CRX); ECR = max(min(CRX − PCRX,40),0); and PCRX = 0.62*PCRA + 0.39*PCRW.

These values are then modified by the following maintenance treatments:

- Patching
- Preventive
  - slurry seal
  - rejuvenation
  - fog seal
- Reseal
  - surface treatment
  - slurry seal
- Overlay
  - hot mix
  - cold mix
- Reconstruction

Following maintenance treatments, distress values are updated and become inputs for the next period of the analysis.

HDM Calibration

Extensive runs were made of AGENCYF in an attempt to calibrate the model using data from the Nevada Maintenance Management Study conducted by Butler (*B-11*) and data from sections set up during this study. Rates of change were calculated for percent of area with fatigue cracking from data collected in 1984 and 1985. The percent change in percent cracking and the percent change in severity were plotted against pavement age since rehabilitation, 18-kip (80 kN) equivalent single axle loads for 1984, and cumulative 18-kip (80 kN) single axles since the last major rehabilitation. The change in severity was calculated by multiplying the percent area with low severity fatigue cracking by 1, moderate severity by 2, and high severity by 3. These values were summed to give an overall severity. Figure B-10 is typical of the results, with no relationship between dependent and independent variables.

A major problem is that there are only two data points for each section. In addition, much of the data needed to run AGENCYF was not readily available. As more data become available, relationships between rates of change in percent cracking and axle loadings may emerge.

An attempt was then made to calibrate AGENCYF using the relationships developed by Butler in the Nevada study. This study produced a series of equations for PSI, fatigue cracking and linear cracking vs pavement AGE. There are two sets of curves for each pavement type and traffic, one is for a high maintenance scenario such as resealing every 2 to 5 years, while the other is for sealing at intervals of 7 years or more.

Nevada sections for which no major maintenance had occurred were used to calibrate HDM output. Seven sections had not received major maintenance between the surveys: NV2, NV3, NV12, NV13, NV14, NV16, NV17. AGENCYF input files were created and calibration runs made. Figures B-11 through B-17 show the high and low maintenance relationships developed by Butler for PSI vs AGE with output of the AGENCYF superimposed.

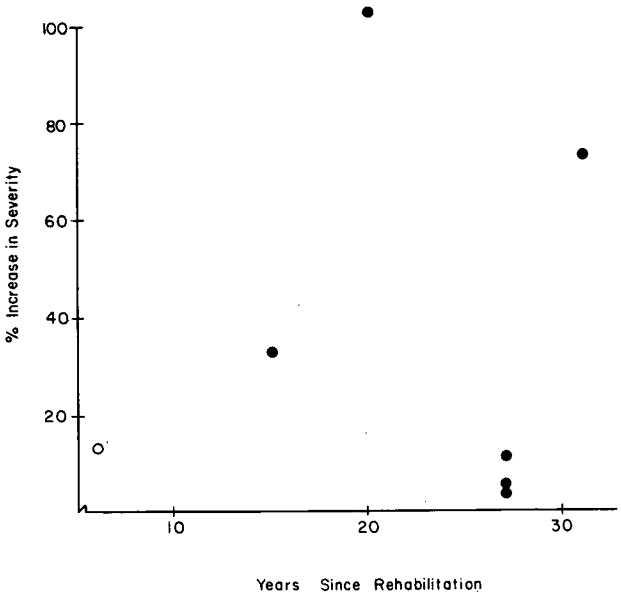


Figure B-10. Change in cracking severity with time.

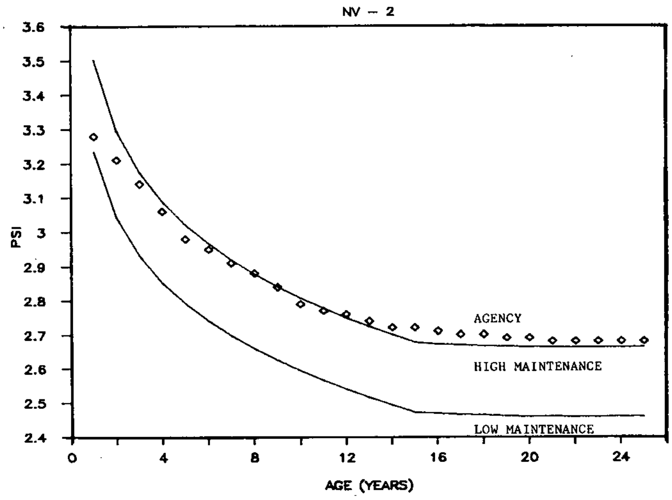


Figure B-11. HDM predictions for Nevada section 2.

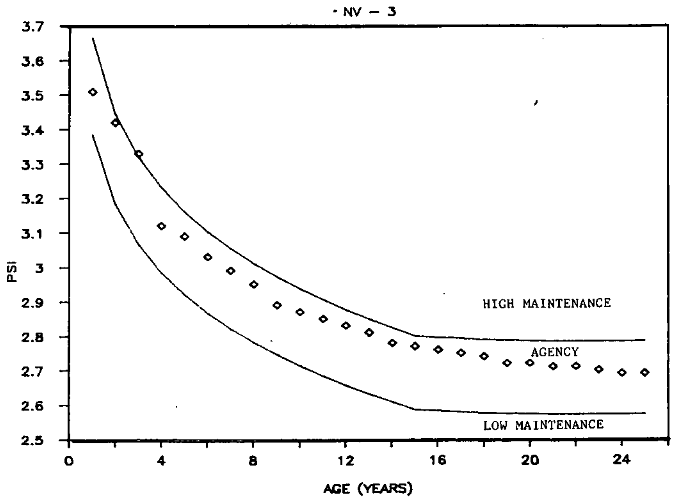


Figure B-12. HDM predictions for Nevada section 3.

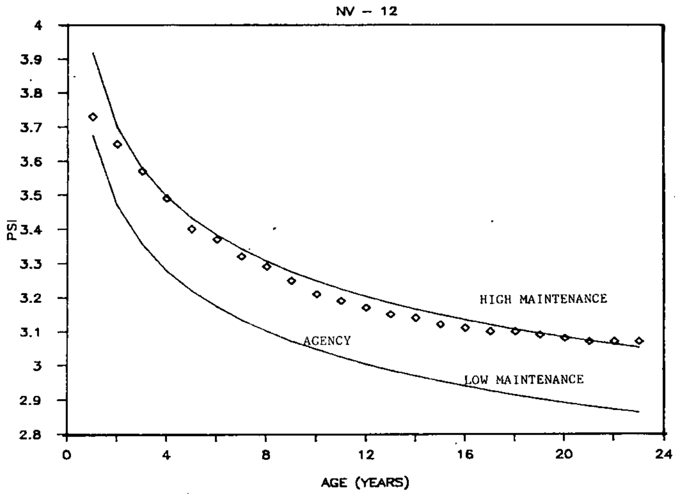


Figure B-13. HDM predictions for Nevada section 12.

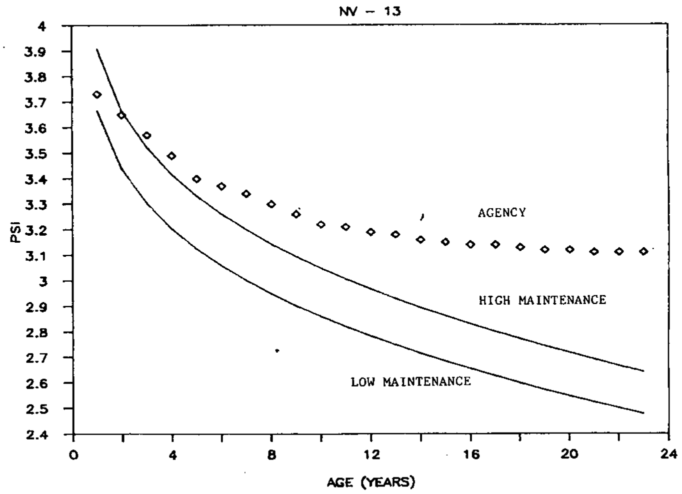


Figure B-14. HDM predictions for Nevada section 13.

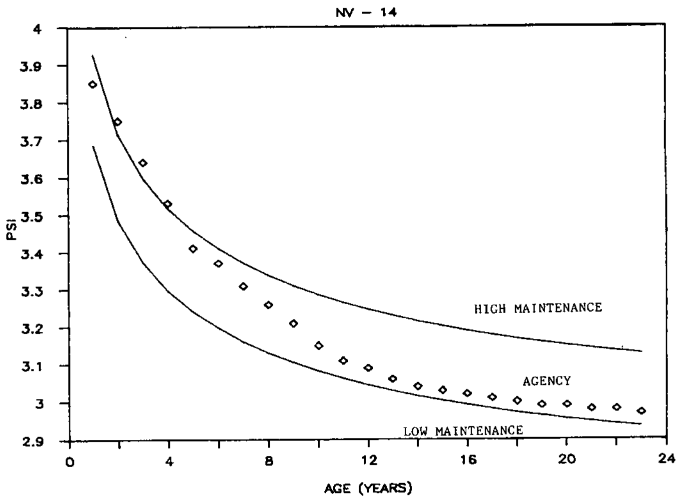


Figure B-15. HDM predictions for Nevada section 14.

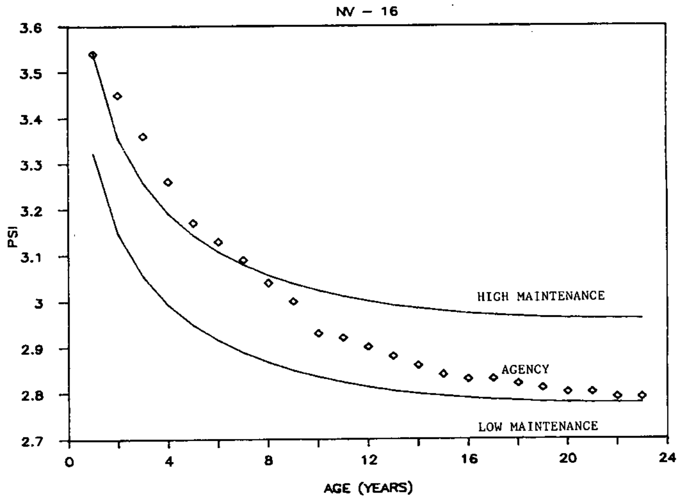


Figure B-16. HDM predictions for Nevada section 16.

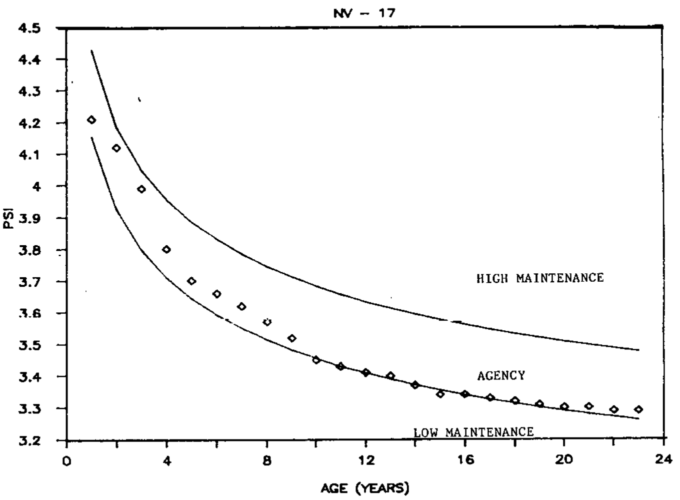


Figure B-17. HDM predictions for Nevada section 17.

Two new calibration constraints were developed in order to change the shape of the curves. These constants were applied to the calibration constants already in the models for general progression of roughness and for environment effects on roughness.

The thinking behind these new constants was that the roughness-related deterioration due to environmental factors is at its highest rate early in the life of the pavement. Environment deterioration after a reseal should be to the seal coat to a great extent.

The lines representing the equations developed by Butler are composite curves and should be thought of as bounds for relatively high and low maintenance scenarios.

Of the seven sections six fit the shape of the bounds well. AGENCYF predicted significantly less loss of PSI. This discrepancy appears to be due to rutting on the section.

Most of the Nevada sections displayed little or no rutting. In order to make the rutting output fit these sections, the rutting calibration constant was low. As a result the predicted rutting for section NV13 was approximately 50 percent low, with an accompanying high prediction of PSI.

IMPACT COMPUTER PROGRAM ALGORITHM

Maintenance strategies influence road users in two ways. First, road surface conditions affect vehicle operating costs, accidents and user comfort. Second, the occupancy of a pavement or bridge deck for maintenance or rehabilitation interferes with traffic operations creating increased vehicle-operating costs, higher accident risks, delays, and motorist inconvenience. Road occupancy also affects the nonroad user because interfering with normal traffic flow creates stop and go operations that raise the level of vehicle-contributed air pollution.

Program IMPACT computes the adverse effects (consequences) to road users and nonusers for any maintenance strategy. The program is divided into two routines, one that addresses the influence of road surface conditions on user consequences and a second that evaluates traffic interference consequences.

Surface Condition Routine

The road surface condition considered is pavement or bridge deck roughness. The roughness measurement unit used is present serviceability index (PSI) as defined by Carey and Irick at the American Association of State Highway Officials (AASHO) Road Test that was conducted between 1956 and 1961 at Ottawa, Illinois (*B-3*).

The surface condition routine computes accidents, comfort, loss time, and vehicle-operating costs corresponding to the road roughness resulting from the application of maintenance.

Road-user costs exist under the most ideal conditions. Program IMPACT evaluates the influence of different maintenance strategies on road-user costs. To maximize the sensitivity of the analysis, the user-costs associated with ideal conditions are not included. As an analogy, consider the depth of an ocean as being equal to the user costs associated with ideal conditions. As surface conditions worsen, waves are created. The poorer the surface, the higher the wave. We compare the depth of the waves for different maintenance strategies.

The routine computes the consequences for a defined maintenance strategy. From these consequences are subtracted the consequences associated with using the road under ideal conditions. Ideal conditions are defined as a road surface condition with a PSI value of 4.5 for an analysis cycle.

Vehicle Operating Costs (VOC). Based on a study by Zaniewski et al. (*B-12*), a microcomputer program "VOC" was developed to generate vehicle operating consumptions for the following parameters:

- Fuel consumption, Gallons
- Oil consumption, Quarts
- Tire wear, % wear
- Maintenance and Repair, % of average costs
- Depreciation, % of average costs

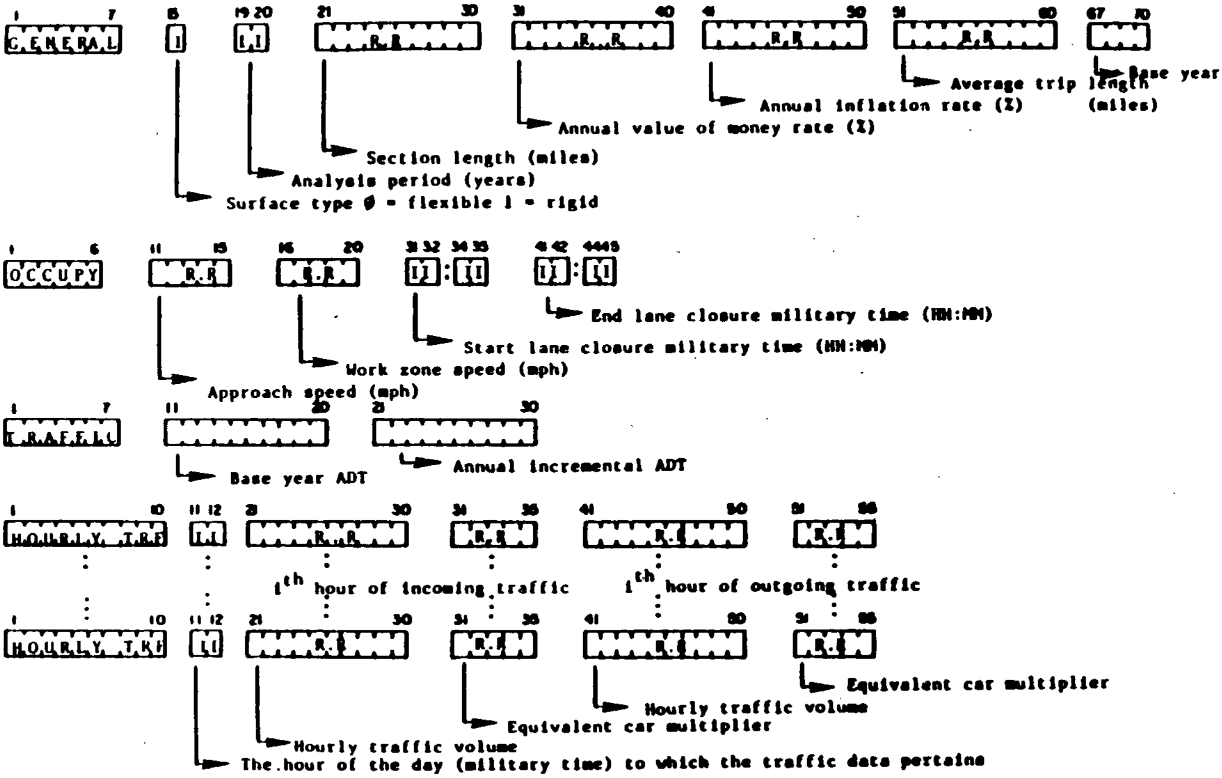
These consumptions are calculated under conditions of constant speed, deceleration, and acceleration using parameters of starting speed, ending speed, and time for each roadway section for each of eight vehicle classes:

- Small Automobile
- Medium Automobile
- Large Automobile
- Pickup Trucks
- 2-Axle Single-Unit Trucks
- 3-Axle Single-Unit Trucks
- 2-Axle Combination Trucks
- 3-Axle Combination Trucks

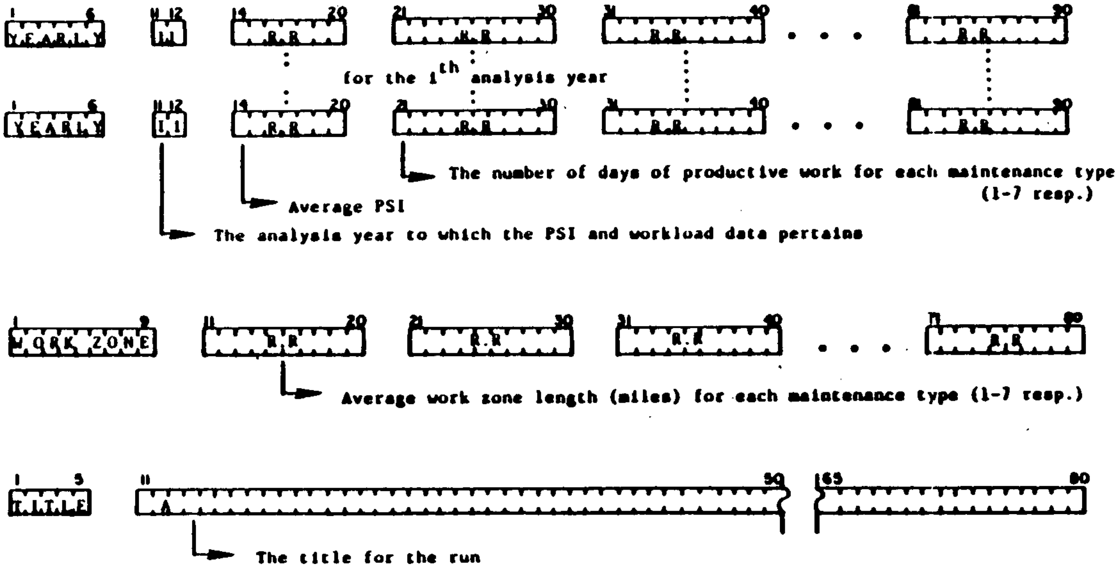
A series of tables were generated using the microcomputer program VOC and included in the program IMPACT. The tables provide vehicle consumptions by vehicle class, speed, and speed changes for tangent-zero grade sections of road. Also taken from the Zaniewski et al. report are a series of factors that reflect the effect of surface roughness on each consumption parameter. These factors are incorporated in the program IMPACT in equation form.

The surface condition, in PSI units, is known annually based on output from the program AGENCY. The surface condition routine uses these PSI values as inputs together with inputs on unit costs of tires, maintenance and repair, and vehicle purchase price. Table B-8 shows these required program inputs.

Table B-8. Input requirements for program IMPACT.



R.R = Real = If no decimal then right justify
A = ALPHANUMERIC
I = INTEGER = Right justify



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A = ALPHANUMERIC
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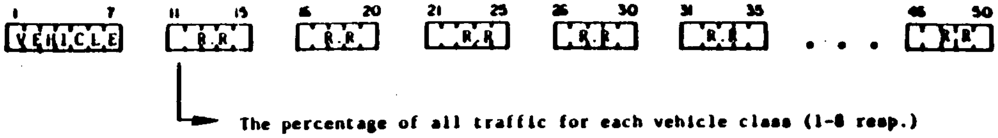
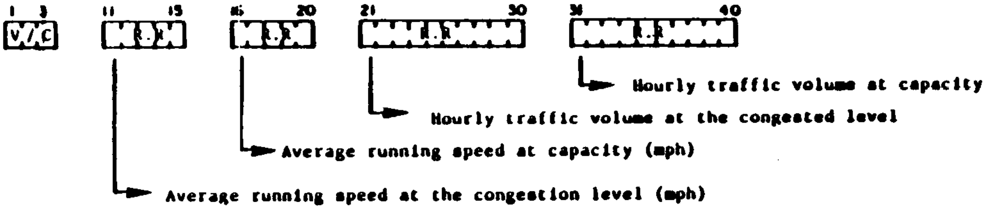
Table B-8. Continued



The percentage of all traffic for each vehicle class (1-8 resp.)

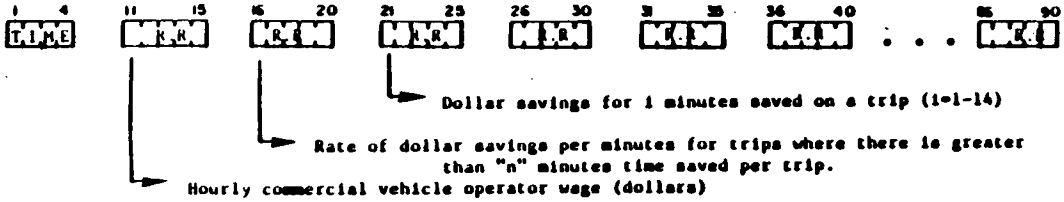


Hourly traffic volume at capacity

Hourly traffic volume at the congested level

Average running speed at capacity (mph)

Average running speed at the congestion level (mph)

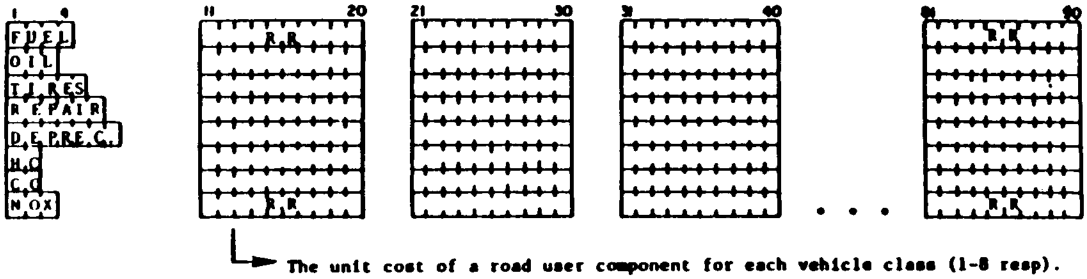


Dollar savings for i minutes saved on a trip (i=1-14)

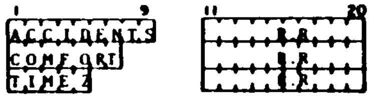
Rate of dollar savings per minutes for trips where there is greater than "n" minutes time saved per trip.

Hourly commercial vehicle operator wage (dollars)

R.R = Real = If no decimal then right justify
A = ALPHANUMERIC
I = INTEGER = Right justify

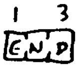


The unit cost of a road user component for each vehicle class (1-8 resp).



Road user Component	Unit Cost Units
Fuel	$/gallon
Oil	$/quart
Tires	$/tire
Repair	$ spent per 1000 miles traveled
Depreciation	New vehcile price ($)
HH Emissions	$ value / ton of emission
CO Emissions	$ value / ton of emission
NOX Emissions	$ value / ton of emission
Accidents	$/accident
Comfort	Multiplier to the programs generated costs
Time2	Multiplier to the costs on the "TIME" card

R.R = Real = If no decimal then right justify
A = ALPHANUMERIC
I = INTEGER = Right justify



Vehicle operating costs are calculated for each year's traffic across the entire road's length. A roughness multiplier factor is then applied which produces the road-user cost increment for the current year's PSI relative to a PSI of 4.5

$$DOC = CR \times UC \times 1000 \times ADT \times DIST \times PSI_f$$

where: DOC = differential vehicle operating costs; CR = consumption rate from VOC table look-up; UC = unit cost of consumption item; ADT = annual average daily traffic; PSI_f = difference of PSI factors at a level of 4.5 versus current year's PSI (these factors are from Table B-9); and DIST = section length in miles.

In calculating roughness-affected road user costs in any one year, the entire year's traffic across the section length is considered. This is done because changes in roughness of the road affect each and every vehicle for the entire road mileage.

Time. The effect of road roughness on vehicle speed is computed from the following equation based on a regression of "VOC" output shown in Table B-10:

$$SF = 1 - 0.001 \times [0.606 \times PSI + 0.391 \times PSI^2 \times S]$$

where: SF = road surface factor; PSI = current PSI where $PSI \leqq 4.5$; and S = average running speed bounded by 15 mph and 35 mph.

These factors were used to compute average vehicle running speed annually in the routine which together with trip length forms the basis for computing the value of time lost due to surface roughness.

The value of time for passenger cars is based on the SRI report, "The Value of Time Saved by Trip Purpose" (*B-13*), where the value of time was shown to be dependent on the amount of time lost, motorists' average income level and trip purpose. A composite income level is defined for the traffic stream, and distribution of trip purposes is fixed.

The computation of the value of loss time involves a small algorithm in the program that:

1. Determines average running speeds as a function of the volume/capacity ratio and surface roughness for roughnesses of 4.5 PSI and the analysis year PSI.
2. Using the two roughness-affected average running speeds, computes the annual hours of time loss per section for one year's traffic.
3. Computes the time lost per trip based on the average running speeds and an average trip length input.
4. Establishes loss time values for each trip, expanding to annual time loss.

Accidents. Accident costs are calculated using a modified version of the free flow accident formula taken from Zaniewski et al. (*B-12*). This results in the following equation:

$$DA = 0.292 \times PSI_f + 1.14$$

where DA = differential annual accidents per 10^6 vehicle-miles, and PSI_f = 4.5 − current year's average PSI.

User Comfort. User comfort is based on a study by Zegeer et al. (*B-12*) and calculated as follows:

Table B-9. Speed adjustment factors for surface conditions.

		F			
PSI	ARS*> 35	ARS = 30	ARS = 25	ARS = 20	ARS < 15
1.0	0.86	0.90	0.93	0.97	1.0
1.5	0.89	0.92	0.95	0.97	1.0
2.0	0.97	0.94	0.96	0.98	1.0
2.5	0.94	0.95	0.97	0.98	1.0
3.0	0.95	0.97	0.98	0.99	1.0
3.5	0.97	0.98	0.98	0.99	1.0
4.0	0.98	0.98	0.99	0.99	1.0
4.5	0.99	0.99	1.00	1.00	1.0
5.0	1.0	1.0	1.0	1.0	1.0

* Average Running Speed

Table B-10. Factors relating road surface condition to the consumption of tire, maintenance, repair, and depreciation.

Serviceability Index	Passenger Cars and Pickup Trucks	Single Unit Trucks 2-S2 & 3-S2 Semi's
1.0	2.40	1.67
1.5	1.97	1.44
2.0	1.64	1.24
2.5	1.37	1.16
3.0	1.16	1.07
3.5	1.00	1.00
4.0	0.86	0.95
4.5	0.76	0.92

Tire expense adjustment factors for roadway surface condition

Serviceability Index	Passenger Cars & Pickup Trucks	Single Unit Trucks	2-S2 and 3-S2 Semi Trucks
1.0	2.30	1.73	2.35
1.5	1.98	1.48	1.82
2.0	1.71	1.30	1.50
2.5	1.37	1.17	1.27
3.0	1.00	1.00	1.00
3.5	1.00	1.00	1.00
4.0	0.90	0.94	0.92
4.5	0.83	0.90	0.86

Maintenance and repair expense adjustment factors for roadway surface conditions.

Serviceability Index	Passenger Cars & Pickup Trucks	Single Unit Trucks	2-S2 and 3-S2 Semi Trucks
1.0	1.14	1.33	1.32
1.5	1.09	1.23	1.22
2.0	1.06	1.15	1.14
2.5	1.04	1.09	1.09
3.0	1.02	1.04	1.04
3.5	1.00	1.00	1.00
4.0	0.99	0.97	0.97
4.5	0.98	0.94	0.94

Use related depreciation adjustment factors for roadway surface condition.

$$DRC = 0.0053 \times (PSI_r) \times ADT \times DIST \times 365$$

where: DRC = differential road comfort; PSI_r = 4.5 − current year's average PSI; ADT = average annual daily traffic; and DIST = section length (miles), but not less than zero.

Traffic Interference Routine

This routine computes the road user consequences created when one lane of a two-lane road is closed to traffic. These consequences are compared to the consequences accumulated while driving on the road without work zone interference.

When a maintenance work zone is installed, vehicles must slow down or stop before passing through the work zone area. To calculate the resulting consequences, a vehicle velocity/distance profile is defined for both conditions:

1. Normal traffic—no interference
2. Traffic interference—created by work zone

Velocity/Distance Profile Algorithm. For a one-lane closure on a two-lane road, simulated vehicle travel is as illustrated in Figure B-18. The velocity/distance profile in Figure B-18 takes place when there is a flagman on either side of the work zone halting traffic. All vehicles, on approaching the work zone, must stop for the flagman. Eventually, the queued vehicles are allowed through the work zone at a restricted velocity. On leaving the work zone, they accelerate until reaching the approach velocity.

There are two velocities, the work zone velocity and the approach velocity. The work zone velocity is an input to the algorithm and is the average speed motorist obtain while driving adjacent to the work zone. The approach velocity is calculated from five user inputs. These inputs are approach speed, congestion speed, speed at traffic capacity, congestion hourly traffic, and hourly traffic volume at capacity. Figure B-19 shows how approach speed is calculated for any volume of traffic.

All accelerations and decelerations are constant 4.5 (miles/hr)/sec.

Distance is calculated directly from velocity, acceleration, and queue length. This is illustrated in Figure B-18.

Queuing Algorithm. Queuing on a two-lane road with a one-lane closure is based on simulating two flagmen working in conjunction, each on a different side of the work zone. This simulation is divided into four repeating events:

D Flagman A allows queued traffic to pass through the open lane until all queued traffic has passed. He then blocks his lane of traffic.
A The last queued vehicle released by flagman A travels through the work zone.
B Flagman B (for the opposing traffic) allows queued vehicles to enter the work zone until all queued traffic passes him. He then blocks his lane of traffic.
C The last queued vehicle released by flagman B travels through the work zone.

The four subcycles are repeated until the work zone is removed. Vehicles in both directions queue during three subcycles. Figure B-20 shows the queuing function over time for both directions of traffic, and the area under the curve is the total hours queued across all traffic.

The queuing algorithm also calculates the average queue length. The effective work zone distance across which vehicles travel at the work zone speed is a function of the average maximum length of the queue as well as the distance it takes a vehicle to accelerate from zero up to the work zone velocity.

All traffic is converted into passenger car equivalents (PCE) for the simulation. Queue length equals the number of PCEs in the queue multiplied by 20 ft.

For either direction of traffic, the average length that a vehicle is back in the queue is one-half the maximum queue length. Maximum queue lengths happen once per cycle (at the end of subcycle C for incoming traffic). Averaging maximum queue lengths across cycles and directions during the closure period and dividing by two gives the average queue length.

Traffic Interference Consequences. To apply the traffic interference algorithm to each road maintenance strategy, it is necessary to apply the traffic interference algorithm to each maintenance activity performed during the year, across the period of time during which the activity is performed. Thus, for each year in the analysis period, this program iterates the traffic interference algorithm across maintenance activities. All inputs to the traffic interference algorithm are constant across time, although the number of hours of closure per year and the maximum work zone length vary by maintenance activity. The annual consequences by maintenance activities are summed across activities yielding the total annual traffic interference consequences.

The consequences are divided into two categories, vehicle-operating costs and other impacts. Vehicle-operating costs are quantified for the following consumptions:

1. Fuel
2. Oil
3. Tire wear
4. Vehicle maintenance and repair
5. Vehicle—depreciation

The other impacts quantified are:

1. HC emissions
2. CO emissions
3. NOX emissions
4. Time costs and interference time
5. Accident costs

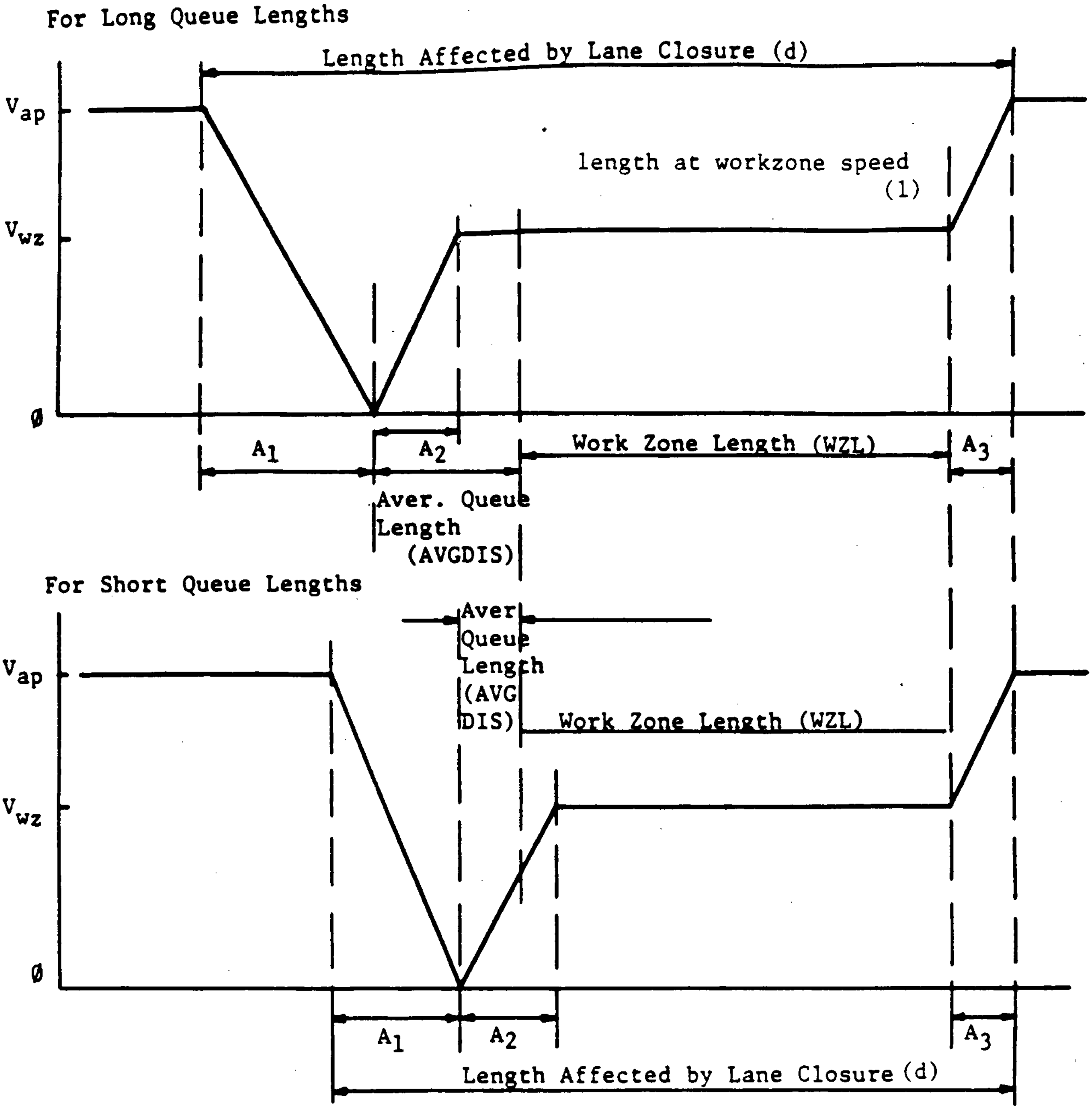
The differentials between these ten impacts under work zone conditions versus a free flow condition are calculated. Vehicle consequence differentials for the first eight of ten impacts are calculated using the constant velocity and speed change tables established by Zaniewski et al. These tables provide average consumption rates at a PSI level of 3.5. The rates are used to calculate costs:

$$Costs = Consumption\ Rate \times Amount \times Unit\ Cost$$

The differential costs are calculated in three parts:

1. Differential costs while maintaining a constant work time speed versus the free flow speed.
2. Excess cost due to a speed change cycle.
3. Costs due idling.

As can be seen in Figure B-18 a vehicle when affected by the lane closure is always in one of these three states.



Where:

$$A_1 = \frac{V_{ap}^2}{2a}$$

$$A_2 = \frac{V_{wz}^2}{2a}$$

$$A_3 = \frac{V_{ap}^2 - V_{wz}^2}{2a}$$

V_{ap} = Approach Velocity (mph)

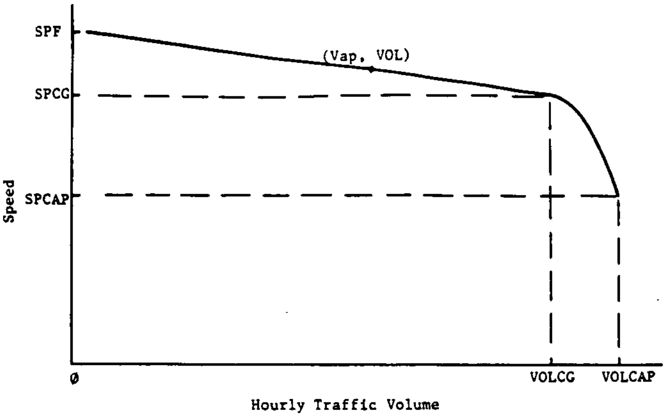
V_{wz} = Work Zone Velocity (mph)

a = Constant Acceleration/Deceleration rate (4.5 mph/sec)

$d = A_1 + AVGDIS + WZL + A_3$

$l = WZL + AVGDIS - A_2$

Figure B-18. Simulated velocity/distance profile for one lane closure on a two-lane road.



This curve shows approach speed (Vap) as a function of the hourly traffic's volume (VOL) to calculate approach speed from volume five parameter's need to be known which are user input's to the algorithm.

SPF	Speed limit (mph)
SPCG	Congestion speed (mph) - default is 40
SPCAP	Speed at traffic capacity (mph) - default is 30
VOLCG*	Congestion hourly traffic volume - default is 1600
VOLCG*	Hourly traffic capacity - default is 2000

* Across both directions for two lane roads.

Figure B-19. Calculation of approach speed as a function of hourly traffic volume.

Under free flow or constant speed conditions, the "Amount" is calculated by multiplying the total traffic affected by the road lane closure by the mileage across which constant speed was maintained.

In simulating a one-lane closure on a two-lane road, all vehicles slow down, find the free flow speed, and stop for a flagman. After stopping, they accelerate to the work zone speed and on leaving the work zone accelerate to free flow speed. As such, all accelerations and decelerations are aggregated into one speed change cycle from the free flow velocity to zero and back again. At this point the "Consumption Rate" for the speed change cycle can be found by table look-up.

The "Amount" needed in the speed change cycle cost calculation is the total number of vehicles affected by the lane closure.

In the idling mode, only fuel costs are considered. "Consumption Rate" is fuel expended per hour. The "Amount" is the total idling time (in hours) across all vehicles affected by the lane closure. Total idling time is the average vehicle's idling time multiplied by the number of vehicles affected by the lane closure.

Across all the cost calculation methods, the unit cost component is established by the engineer and input to the program.

Accidents. Accident costs are derived using the following consumption formulas:

$$A = 2.454 - 0.292 * \text{PSI (Ref. } \textit{B-10}\text{)}$$
$$AA = .307*A \text{ (Ref. } \textit{B-13}\text{)}$$

where: A = accidents per 10^6 vehicle-miles; ADT = average annual daily traffic, in thousands; PSI = roughness which is set to 3.5; and AA = accident rate excess due to traffic interference.

Time Costs. Time cost differentials are calculated by summarizing the value of time across all traffic affected by the lane closure. As indicated earlier, the value of time is a function of amount of time saved on a trip as well as the income level of the motorist. To calculate the cost of lost time, the algorithm varies the value of time relative to the time lost per trip but uses a single average income level for all traffic affected by the closure zone. Travel time is estimated for free flow conditions as well as during the lane closure. The travel time under free flow conditions, t_{ff}, is calculated by multiplying the free flow velocity by the distance across which traffic is affected by the closure. The calculation of distance is illustrated in Figure B-18.

The travel time under closure conditions is calculated by simulating a velocity/distance profile for the average vehicle traveling through the work zone. This profile is illustrated in Figure B-18 and is made up of three modes: (1) the constant velocity mode, (2) the acceleration/deceleration mode, and (3) the idling mode.

During constant work zone velocity time is equal to velocity multiplied by distance:

$$t_{cs} = d/V_{WZ}$$

where: t_{cs} = work zone constant velocity mode time, hours; V_{wz} = work zone velocity, miles/hr; d = WZL + AVGDIS − $V_{wz} \times V_{wz}/(2a)$, miles; WZL = work zone distance between the two flagmen, miles; AVGDIS = half the average maximum queued length, miles; and a = constant acceleration/deceleration rate, miles/hr^2.

In the acceleration/deceleration mode:

$$t_{acc} = 2 \times V_{ap}/a$$

where: t_{acc} = acceleration mode time, hours; V_{ap} = free flow velocity, miles/hr; and a = the constant acceleration/deceleration rate, miles/hr^2.

The third component of road-lane closure time is the time spent in a queue, t_q, which is the area under the curve shown in Figure B-20.

Total time lost due to closure is then:

$$\text{Time lost to closure} = t_{cs} + t_{acc} + t_q - t_{ff}$$

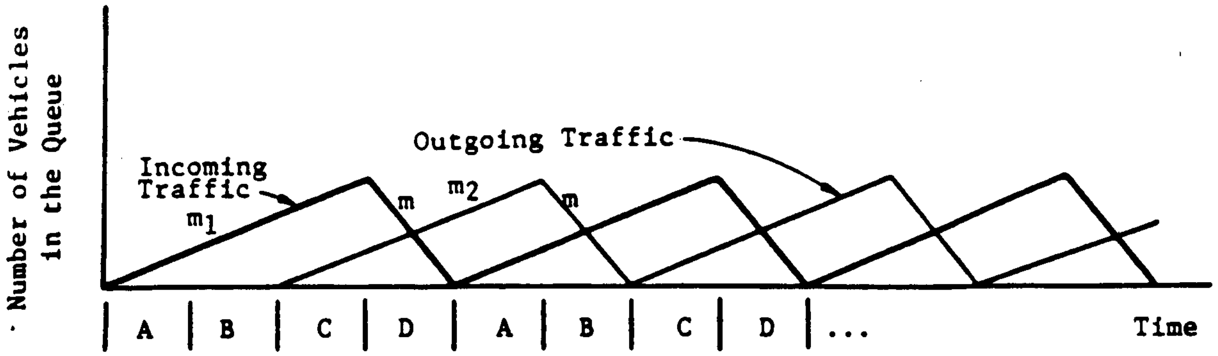
REFERENCES

B-1. Rauhut, J. B., Lytten, R. L., Darter, M. I., "Pavement Damage Functions for Cost Allocation." *FHWA Report No. FHWA/RD-84/017* (June 1984).

B-2. Riggins, M., Lytton, R. L., Garcia-Diaz, A., "Developing Stochastic Flexible Pavement Distress and Serviceability Equations." Texas Transportation Institute (Aug. 1984).

B-3. "The AASHO Road Test—Report 5: Pavement Research." *Special Report 61E,* Highway Research Board (1962).

B-4. Butler, B. C., Jr., "Economic Analysis of Roadway Occupancy for Freeway Pavement Maintenance and Re-



A cycle is the time between two zero queue situation for one direction's traffic and is composed of subcycles A, B, C, & D.

Subcycle	Time Formula	Definition
A	$\frac{WZL}{Vwz} \times 3600 + 10$	The last queued outgoing vehicle travels through the workzone.
B	$\frac{1.}{1./2.1 - \frac{EVOL_2}{3600}}$	The second flagman (for the incoming traffic) is allowing vehicles to go into the workzone. He then blocks his lane of traffic
C	$\frac{WZL}{Vwz} \times 3600 + 10$	The last queued vehicle incoming travels through the workzone.
D	$\frac{1.}{1./2.1 - \frac{EVOL_1}{3600}}$	The first flagman (for the outgoing traffic) is allowing vehicles to go into the workzone. He then blocks his lane of traffic.

Where:

WZL = Workzone Length (miles)
Vwz = Workzone Velocity (mph)
$EVOL_1$ = Equivalent car hourly traffic volume for outgoing traffic.
$EVOL_2$ = Equivalent car hourly traffic volume for incoming traffic.

And:

10 Seconds is the average waiting time between the last vehicle passing out of the workzone and the first queued vehicle starting to accelerate.
m^{-1} = 2.1 sec./vehicle is the average queue exit rate.
${m_i}^{-1}$ = 3600/$EVOL_i$ is the average queue entry rate per direction (sec/vehicle)

Figure B-20. Queuing as a function of time.

habilitation." *FHWA Report No. FHWA-RD-76-15* (Oct. 1974).

B-5. Bertram D. Tallamy Associates, "Long Range Pavement Maintenance Program Illinois State Toll Highway System." The Illinois State Toll Highway Commission (Mar. 1968).

B-6. SHOBER, S., and JOHNSON, K., "Experimental Rehabilitation of Jointed Portland Cement Concrete Pavement." Wisconsin Department of Transportation (Feb. 1983).

B-7. THORNTHWAITE, C. W., "An Approach Toward a Rational Classification of Climate." *The Geological Review,* Vol. 38, No. 1 (1948).

B-8. Empresa Brasileira de Planejamento de Transportes, GEIPOT, "Research on the Interrelationships Between Costs of Highway Construction, Maintenance and Utilization." Final Report, UNDP Project BRA-74/012, Brasilia (1981).

B-9. QUEIROZ, C. A. V., "A Procedure for Obtaining a Stable Roughness Scale from Rod and Level Profiles." Brazilian Government (Sept. 1971).

B-10. *World Bank Draft User's Manual,* Highway Design and Maintenance Standards Models (HDM-Version III), Personal Correspondence.

B-11. BUTLER, B. C. JR., "Refinement of MMS Flexible Pavement Program Workload Models." Nevada DOT (June 1985).

B-12. ZANIEWSKI, J. P., BUTLER, B. C., JR., CUNNINGHAM, G., ELKINS, G. E., PAGGI, R., and MACHEMEHL, R., "Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors." Final Report, Federal Highway Administration, Washington, D.C. (Aug. 1981).

B-13. THOMAS, T. C., and THOMPSON, G. I., The Value of Time Saved by Trip Purpose." Sanford Research Institute, SRI Project MSU-7362 (Oct. 1970).

APPENDIX C

BRIDGE EVALUATION METHODOLOGY (BLCCA)

LIFE-CYCLE COST ANALYSIS

To allocate bridge maintenance resources in a cost-effective manner, highway officials must be able to determine the effects of different maintenance strategies or actions on bridge cost. Life-cycle cost analysis enables maintenance officials to identify and compare the costs of owning a bridge under alternative maintenance approaches.

To understand how a computer program, called the Bridge Life Cycle Cost Analyzer (BLCCA), and developed by Ernst & Whinney works, it is helpful to be familiar with several key concepts: life cycle cost, inflation, present value, and annualized cost.

Key Concepts

Life Cycle Cost

The life cycle cost of a bridge is the total cost of building and maintaining the bridge over its entire life. The essence of life cycle costing is to evaluate the life cycle cost of alternative construction and maintenance approaches in order to identify the option with the lowest life cycle cost. For example, this technique would enable bridge maintenance officials to compare the costs of such competing options as a "bare bones" or demand maintenance approach resulting in the lowest life cycle cost.

Moreover, the analysis of such alternatives need not be limited to maintenance approaches. Life cycle cost analysis can also be used to compare the costs of two different bridge types: for example, a timber bridge with a relatively low construction cost and short life span, and a reinforced concrete structure with a much larger construction cost, but a longer life. Whether comparing alternative structure types, maintenance approaches, or both, life cycle cost analysis will identify the least costly option. In view of the objectives of Project 14-6, however, the technique's application in the evaluation methodology described here is limited to analyses of alternative maintenance approaches.

Inflation

Because of the effects of inflation, the cost of a hypothetical bundle of goods will generally be greater in 1985 than in 1984. In real terms, however, the cost of the goods may be the same in both years, depending on whether or not the supply and/or demand for the goods has changed. In order to avoid misinterpretation and confusion in comparisons of costs incurred in different time periods, financial analysts routinely distinguish between inflated or "nominal" dollars and constant or "real" dollars. Constant dollars reveal the true change (if any) in the cost of the bundle of goods by factoring out the effects of inflation.

All of the expenditures (except the original construction cost) entered into the Bridge Life Cycle Cost Analyzer program are expressed in constant dollars. That is, the stream of future expenditures that represents the maintenance approach to be analyzed should reflect today's costs. The Cost Analyzer handles the tedious task of converting these amounts to the nominal or inflated dollars amounts that will be spent in future years.

The output of the Cost Analyzer also is expressed in constant, rather than inflated dollars. If inflated dollars were used, the stream of costs incurred over a bridge's life would be a hodgepodge of dollars with different purchasing powers. Maintenance officials could never be sure that the maintenance approach with the lowest cost in nominal dollars is the cheapest alternative in real terms. By converting future costs to constant dollars, the Cost Analyzer enables officials to accurately assess the costs and benefits of maintenance activities performed at different times.

Present Value

If we have a dollar today and invest it at 10 percent, we will have $1.10 next year. Therefore, we would rather have a dollar today than a dollar next year. Similarly, a company that borrows money would rather have a dollar today than a dollar next year. By using that dollar to repay its debts today instead of next year, the company could save the year's interest charges on the dollar.

To account for the fact that the value of cash flows depends on how far in the future they occur, financial analysts normally adjust cash flows using the cost of capital or interest rate. Specifically, they convert all cash flows to their present values. For example, the present value of a dollar spent today is a dollar, but the present value of a dollar spent next year is only $0.91 if the cost of capital is 10 percent. This is because $0.91 is the amount that would, if invested at 10 percent interest today, produce $1.00 a year from now. A company would therefore be indifferent to paying out $0.91 now and paying our $1.00 a year from now.

In general, the value of an interest-earning investment is given by:

$$FV = PV (1 + i)^n$$

where: FV = the value n years in the future, PV = the present value of the principal invested, i = the interest (or discount) rate, and n = the number of years since the investment was made. Rearranging this formula gives: $PV = FV/(1 + i)^n$.

This is the formula used in the Cost Analyzer to find present values. Applying this formula to a one dollar expenditure one year in the future with a 10 percent cost of capital gives $\$1.00/(1 + .10) = \$1.00/1.1 = \$0.91$, as mentioned above.

The foregoing discussion deals with adjusting the future dollar amount to reflect the cost of capital. The previous section talked about making a similar adjustment in future dollar amounts to reflect inflation. What is the relationship between these two adjustments? Inflation is one of the factors that determines the cost of capital. It is therefore useful to think of interest rates as being made up of two components, an inflation rate and a constant dollar or "real" cost of money. This latter component reflects the supply and demand for funds. For example, if the cost of capital is 10 percent and inflation is 7 percent, the constant dollar cost of capital is 3 percent.

The Cost Analyzer computations use both the cost of capital including inflation and the inflation-free cost of capital. The "spread" between these two numbers should be consistent with the user's assumption about future inflation rates, which is also an input to the Cost Analyzer.

Annualized Cost

When the present value of a cost is known, one can find an amount X such that spending X in every year of the bridge's life gives the same present value. The amount X is referred to as the annualized or levelized cost. It is analogous to an annual rent. It is an annual amount, the same for every year of the bridge's life, that covers the cost of building and maintaining a bridge. In other words, it is the *life cycle cost expressed on a per year basis.*

This practice of converting cash flows to an annualized cost for comparison purposes, which has been widely accepted by financial analysts and academicians, is particularly well suited to evaluations of cash flows with unequal lives, such as are likely to occur under different bridge maintenance scenarios (for instance, a repair maintenance approach that increases bridge life to 50 years).

BRIDGE LIFE CYCLE COST ANALYZER

Using the Bridge Life Cycle Cost Analyzer includes the following five steps:

1. Complete an input worksheet listing data and assumptions for the maintenance approach to be analyzed.
2. Run the Cost Analyzer program.
3. Enter the information from the input worksheet.
4. Print desired report(s).
5. Exit the program.

This section explains in some detail how to perform each of the above steps.

Step 1: Input Worksheet

The first step in running the BLCCA program is to organize and collect all data on the input worksheet (Exhibit C-1). This serves the dual purpose of providing a written record of any assumptions made and ensuring that all needed data are available.

Some of the worksheet items are self-explanatory. Explanations for the others are presented below:

4. *Inflation Rates.* The Cost Analyzer allows the user to assume that the rate of inflation will change over time. The current rate (Year 1), the rate in the near future (Year 4), and the rate in the distant future (Year 20) can be specified. The computer assumes that the rate of inflation changes in a straight-line fashion between those 3 years.

5. *Bridge Type.* The user can maintain a list of bridge types (A,B,C, etc.) which have different default lifetimes and maintenance profiles.

6-12. *Maintenance Expenditures.* As it is currently written, the Cost Analyzer explicitly accounts for painting, deck repair, and substructure repair. Any other maintenance expenditures are entered under Category 12, Other Maintenance. However, the program can easily be modified to accommodate additional and/or more specific categories of maintenance activity.

13. *User Cost.* Any user costs can be entered here.

The following list shows the default values for each category:

1. Title—blank
2. Cost of Capital with Inflation—10%
3. Cost of Capital without Inflation—4%
4. Inflation Rates:
   Year 1—6%, Year 4—6%, Year 20—6%
5. Bridge Type—A
6. Expected Life in Years—50
7. Original Construction Cost—0
8. Age in Years—0

EXHIBIT C - 1
BRIDGE LIFE CYCLE COST ANALYZER
INPUT WORKSHEET

1. Title ____________________
2. Cost of Capital with Inflation ______________
3. Cost of Capital without Inflation ______________
4. Inflation Rates:
    Year _____
    Year _____
    Year _____
5. Bridge Type ____________________
6. Expected Life in Years ________________
7. Original Construction Cost ________________
8. Age in Years ____________________

Maintenance Expenditures

	9	10	11	12	13
Year	Painting	Deck Repair	Sub Repair	Other Maint.	User Cost
1					
2					
3					
4					
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					
15					
16					
17					
18					
19					
20					
21					
22					
23					
24					
25					
26					

Maintenance Expenditures
(Continued)

	9	10	11	12	13
Year	Painting	Deck Repair	Sub Repair	Other Maint.	User Cost
27					
28					
29					
30					
31					
32					
33					
34					
35					
36					
37					
38					
39					
40					
41					
42					
43					
44					
45					
46					
47					
48					
49					
50					
51					
52					
53					
54					
55					
56					
57					
58					
59					
60					

9-12. Maintenance Expenditures—0 in each year
13. User Cost—0 in each year.

Step 2: Run The Cost Analyzer Program

The BLCCA program is written in the Advanced Basic Language for the IBM PC microcomputer. The program is stored on a single floppy diskette. To execute the program, the steps listed below should be followed:

1. Put the program disk in the left disk drive (Drive A) on your IBM PC.
2. Put a blank, formatted diskette labeled Data Disk in the right disk drive.
3. Turn on the power for the IMB PC, the monitor, and the printer.
4. The program disk is designed to be "bootable." That is, it automatically loads the operating system, loads BASIC language, and loads the BLCCA program.
5. Initially, two things will happen:
    a. You will be prompted for the current date, enter it in the form MM-DD-YY (e.g., 6-26-84).
    b. You may see the message "Welcome to the Bridge Life Cycle Cost Analyzer." Press the space bar to continue.
6. You will next see the menu of commands available in the Cost Analyzer. The exhibit below shows what this menu looks like.

```
THE FOLLOWING COMMANDS ARE AVAILABLE:
   1) CASE          8) DATA
   2) DELETE        9) DETAIL
   3) EDIT         10) BTDETAIL
   4) EXIT         11) LEVEL
   5) HELP         12) BTLEVEL
   6) INPUT        13) SAVE
   7) INFO
   PLEASE ENTER THE NUMBER OF THE COM-
   MAND YOU WISH TO EXECUTE?
```

7. Simply enter the number of the command you wish to execute. When the command is finished, you will be returned to this menu.

Step 3: Enter Information from the Worksheet

The Cost Analyzer will prompt you for the number of the command you wish to execute. To input data, enter the number 6. The computer will respond by printing:

```
CASE NUMBER ASSIGNED IS: 1 (or the next available
case number)
ENTER THE LINE NUMBER OF THE DATA TO BE
ENTERED (E TO EDIT OR 0 TO STOP)
LINE #:?
```

At this point, type in the worksheet line number of the data item you want to enter and press <ENTER>. (Note that every line on the worksheet is numbered.) The computer will then print the name of the information item and wait for you to type in the value(s). After you supply the values and press <EN-

TER>, it will ask for another line number so you can enter a different piece of information.

A few important rules apply to the data entry process:

1. When entering data, do not use symbols such as $ and %.
2. Commas are used only to separate numbers in a series (such as items 4 and 5). Do not use them within numbers. Example: for ten thousand type 10000 instead of 10,000.
3. Express percentages as decimal fractions. An 8 percent inflation rate would be entered as .08, instead of 8%.
4. You can use as many or as few decimal places as you wish, except that year number and bridge age must be whole numbers.
5. The case title must not exceed 40 characters in length.

Because Items 9–13 may contain several years' values for each line number, data entry is a bit different for these items. Specifically, the computer needs to know in which year to place the value you enter. Therefore, when you tell the computer you want to enter information for one of the last five lines on the worksheet, it will respond with "YR, AMT>?" This means it wants you to type in the year numbered followed by the value. The two should be separated by a comma.

After you have entered one year's value for a particular line, the computer assumes you want to keep entering data for the same line and will continue to request the year and amount (by printing: YR, AMT>?). To tell the computer you are finished with that particular line, enter "0,0". This will bring you back to the line number prompt (Line #:?) so you can enter another line. The example below illustrates the data entry process.

```
THE FOLLOWING COMMANDS ARE AVAILABLE:
1) CASE              8) DATA
2) DELETE            9) DETAIL
3) EDIT             10) BTDETAIL
4) EXIT             11) LEVEL
5) HELP             12) BTLEVEL
6) INPUT            13) SAVE
7) INFO
PLEASE ENTER THE NUMBER OF THE COMMAND
YOU WISH TO EXECUTE? 6
CASE NUMBER ASSIGNED IS: 9
ENTER THE LINE NUMBER OF THE DATA TO BE
ENTERED (E TO EDIT OR TO 0 TO STOP)
LINE # : ? 1
TITLE ? BRIDGE A - SCENARIO 1
LINE # : ? 2
COST OF CAPITAL (INCLUDE INFLATION): ? .16
LINE # : ? 3
COST OF CAPITAL (EXCLUDE INFLATION): ? .09
```

If you make a mistake while entering data, you can correct it using the Cost Analyzer's editing capability.

The data entry process continues as in the foregoing examples until you have entered all the information from the worksheet, skipping any item that does not apply to the case you are studying. After you have entered all the information from your worksheet, type zero the next time the computer asks for a line number. The computer will then return to the command menu.

Step 4: Print Desired Report(s)

There are two commands that can be used to obtain printouts of the results of an analysis. One is LEVEL, which produces a report showing the annualized cost of owning a bridge for every possible service life under the scenario being examined. A sample report is shown in Exhibit C-2. The report indicates the year in which the annualized cost is at a minimum. This is the optimal life of a bridge (from the standpoint of minimizing cost) under this scenario.

It should be emphasized that the amount shown for a given year is not the cost of a bridge in that year alone, but the cost in each and every year up to and including that year. In other words, a bridge maintained to the optimal life of 50 years indicated in Exhibit C-2 would cost $16,718 per year for 50 years.

The other report command, DETAIL, prints a report showing, for any service life you specify, a breakdown of the annualized expenses among six major cost categories. A sample report is shown in Exhibit C-3. For each cost category, the report shows the annualized cost. This is helpful in understanding the relative importance of the cost types and the reasons for changes in the total annualized cost as bridge life varies.

To get either report, simply type in the appropriate command number when the computer asks for a command. When you press <ENTER>, the computer will ask for the case number

EXHIBIT C-2

```
                         CABE * 4

                SAMPLE BLCCA LEVEL REPORT

                 12-11-1984     11:04:52
      ANNUALIZED COST FOR ALTERNATIVE SERVICE LIVES
=====================================================================
REMAINING     ANNUALIZED       REMAINING          ANNUALIZED
LIFE (YEARS      COST         LIFE (YEARS)           COST
=====================================================================
    1         $367200             26               $22318
    2         $187200             27               $21844
    3         $127231             28               $21407
    4         $ 97269             29               $21003
    5         $ 79311             30               $20711
    6         $ 67354             31               $20362
    7         $ 58826             32               $20037
    8         $ 52442             33               $19735
    9         $ 47486             34               $19452
   10         $ 43779             35               $19188
   11         $ 40533             36               $18941
   12         $ 37835             37               $18709
   13         $ 35559             38               $18491
   14         $ 33615             39               $18287
   15         $ 31937             40               $18144
   16         $ 30473             41               $17963
   17         $ 29187             42               $17791
   18         $ 28049             43               $17630
   19         $ 27036             44               $17477
   20         $ 26247             45               $17332
   21         $ 25426             46               $17196
   22         $ 24683             47               $17066
   23         $ 24009             48               $16944
   24         $ 23395             49               $16828
   25         $ 22833             50               $16718

                                           *** Minimum Cost***
```

```
                        EXHIBIT C- 3

                          CABE * 4

                  SAMPLE BLCCA LEVEL REPORT

                  12-11-1984    11:26:11
    COMPOSITION OF ANNUALIZED COST OF MINIMUM COST SERVICE LIFE
                         (YEAR 10)
====================================================================
 COST COMPONENT                 ANNUALIZED        PERCENT
                                   COST           OF TOTAL
====================================================================

CAPITAL INVESTMENTS            $43531/YR            99%

PAINTING                         $248/YR             1%

REPAIRS TO DECK                    $0/YR             0%

REPAIRS TO SUBSTRUCTURE            $0/YR             0%

OTHER MAINTENANCE                  $0/YR             0%

USER COSTS                         $0/YR             0%

                               __________          _____

TOTAL                          $43779/YR           100%
                               ==========          ======
```

(which is the number it assigned immediately after you entered the command INPUT). You can respond with the case number, the letter C (which means you want results for the current case, the case you were just working with), or a zero. Zero indicates that you do not want the report after all and causes the computer to ask for a new command.

After you have specified the case for which you want the report, the Cost Analyzer will print out the LEVEL report, if that is the one you requested. If you requested the DETAIL report, the computer will ask which year you want it for and then will print out the report for the appropriate year. You have the option of entering a specific year, asking for the minimum cost year (the one with the lowest annualized cost), or asking for all years. To illustrate, the series of commands, prompts, and responses shown below produced the DETAIL report in Exhibit C-3.

```
THE FOLLOWING COMMANDS ARE AVAILABLE:
1) CASE                   8) DATA
2) DELETE                 9) DETAIL
3) EDIT                  10) BTDETAIL
4) EXIT                  11) LEVEL
5) HELP                  12) BTLEVEL
6) INPUT                 13) SAVE
7) INFO
PLEASE ENTER THE NUMBER OF THE COMMAND
YOU WISH TO EXECUTE? 9
ENTER 0 TO RETURN TO MAIN MENU
ENTER CASE # (C FOR CURRENT DATA): ? 4
CHOOSE FROM THE LIST BELOW WHICH YEAR TO
PRINT.
0 STOP 1) ENTER SPECIFIC YEAR 2) MINIMUM COST
YEAR 3) ALL YEARS ? 1
ENTER 0 TO STOP
ENTER YEAR FOR DETAIL REPORT (1-50)? 10
P OR S? P
```

Step 5: Exit from BLCCA

To end your session on the computer, use the EXIT command; that is, type "4" when the computer asks you for a command number. (If you have been working with a case and have not stored it in the computer's memory, the Cost Analyzer will ask you if you want to store it.)

After you enter the EXIT command, you will be in the BASIC language. You should remove both diskettes and carefully store them for future use. It is advisable to make a copy of your data diskette on a periodic basis. You can do this with the DOS COPY command (refer to the IBM Disk Operating System manual if you are not familiar with the command).

Computational Procedures

The Bridge Life Cycle Cost Analyzer performs computations in the series of five steps shown below:

1. Find the missing values in the table of annual costs.
2. Inflate all dollar amounts.
3. Find the present value of each expense category.
4. Convert each present value to an equivalent annual amount.
5. Sum the equivalent annual amounts over all cost categories to determine the total annualized cost of the cash flow being analyzed.

The first two steps transform the input data into a complete tabulation of year-to-year bridge construction and maintenance costs. These costs are expressed in inflated dollars. First, the computer uses linear interpolation to find values for years not specified directly by the user. The dollar amounts are then converted from constant to inflated dollars.

Steps 3 through 5 convert the tabulation of bridge maintenance costs into a single annualized cost figure. In Step 3, the Cost Analyzer finds the present value of the year-by-year costs tabulated in Step 2. In Step 4, the present values of each stream of costs are converted to annualized amounts. Finally, Step 5 sums the annualized cost figures for all cost categories to find the total annualized cost of building and maintaining a bridge under the approach being analyzed. Each of these steps is discussed in more detail below.

Step 1: Missing Values

The computations begin after the user has entered the appropriate data from the input worksheet (Exhibit C-1). With the possible exception of user cost, it is unlikely that the costs entered under Items 9 through 13 will be incurred in each and every year of a bridge's life. Therefore, costs should only be entered for those years in which maintenance will be performed.

As a convenience to the user, the Cost Analyzer uses a straight-line interpolation to assign costs to years for which maintenance and other costs are not entered manually. For example, if a maintenance official believes that the user cost associated with a given maintenance approach will steadily increase from $1,000 in the fifth year of a bridge's life to $2,000 in the ninth year, he need only enter $1,000 in year 5 and $2,000 in year 9. The program will automatically interpolate cost figures for years 6 through 8 of $1,250, $1,500, and $1,750.

Although this feature is useful for generating annual user costs to be incurred over the life of a bridge, it is generally to be avoided when entering maintenance expenditures because few bridges receive the same kind of maintenance several years in succession. For example, a bridge would not be painted, either at a constant cost or increasing cost, 5 years in a row. Therefore, when entering painting expenditures in, say, years 4 and 8, this linear interpolation feature should be overridden by manually entering a value of zero for Item 9 (painting) in years 5–7.

Another convenient feature of the Cost Analyzer is that the program automatically supplies missing values for all years before and after the years in which costs are entered. For years prior to those for which the user supplies costs, the computer automatically supplies a zero. For years after the ones for which the user supplies costs, the computer finds the last year for which the user supplied a cost and uses that value for all subsequent years. For example, suppose a bridge could have a life of up to 50 years, but that the user only specifies values for years 10 and 40. The Cost Analyzer will supply zeros for years 1 through 9 and interpolate cost figures for years 11 through 39. For years 41 to 50, the program will use the cost figure supplied by the user for year 40. Again, this feature can be manually overridden by entering zero expenditures in years 11–39 and 41–50. This feature's value lies primarily in generating annual amounts of costs, such as user costs, which will be incurred several years in succession.

Step 2: Inflation

The cost inputs to the Cost Analyzer are expressed in constant dollars. The program converts these costs to nominal or inflated dollars using the default inflation factors, or rates supplied by the user in Item 4 of the input worksheet.

The inflation rate need not be the same in all years. The user specifies the current, near-term, and long-term rates, which are automatically assigned to Years 1, 4, and 20. The computer then finds the inflation rates in the other years using straight-line interpolation. For example, if the user enters the inflation rates .10, .07, .07, the program will use a 10 percent inflation rate in year 1, 9 percent in year 2, 8 percent in year 3, and 7 percent in all subsequent years.

The program assumes the entered amounts are in Year 1 dollars, so no inflation adjustment is applied to the Year 1 amounts. Year 2 dollar amounts are inflated by multiplying them by a factor equal to:

$$1 + (\text{Yr. 2 inflation rate})$$

The Year 3 amounts are inflated using the following factor:

$$[1 + (\text{Yr. 2 inflation rate})]\ [1 + (\text{Yr. 3 inflation rate})]$$

The inflation factor for each year is found by adding 1 to the inflation rate for that year and then multiplying by the factor for the previous years.

Step 3: Present Value

In this step, each component of the steam of costs incurred under the maintenance approach being analyzed is converted to its present value using the current cost of capital as a discount rate. Because the amounts being discounted are expressed in inflated dollars, the discount factor should be the directly measured cost of capital, which reflects the user's assumptions concerning inflation.

The Cost Analyzer converts future amounts into their present value at the beginning of Year 1. (This point in time is designated as Year 0.) All expenditures are treated as occurring in the middle of the year (essentially the same as assuming that the expenditures are spread uniformly over the year). Thus, Year 1 amounts are discounted over a period of 6 months. That is, they are divided by:

$$\left(1 + \frac{\text{discount rate}}{2}\right)$$

For other years, the discount factor is:

$$\left(1 + \frac{\text{discount rate}}{2}\right)\left(1 + \text{discount rate}\right)^{n-1}$$

where n is the year number.

Step 4: Annualized Cost

Once the present value of a stream of costs is known, one can find an amount X such that spending X in every year of a bridge's life gives that present value. Mathematically, this problem can be expressed as follows:

$$\begin{aligned} PV &= 1+r/2 + (1+r/2)(1+r) + (1+r/2)(1+r)^2 \\ &\quad + \ldots (1+r/2)(1+r)^n \\ &= X\,(1+r/2)(1+r)^{n-1} \\ &= X \cdot A_{yr} \end{aligned}$$

where: PV = the present value of the stream of future costs; X = the annualized cost of the stream; n = the year in which costs are incurred; y = the life of the bridge; r = the discount rate; and A_{yr} = the annuity factor for bridge life y and discount rate r.

The annuity factor A_{yr} can be computed for any bridge life y and discount rate r. The Cost Analyzer first calculates the appropriate annuity factor. It then divides the present value by the annuity factor to find the equivalent annual cost (in constant dollars) of the stream of costs (since $PV = X \cdot A_{yr}$, $X = PV/A_{yr}$).

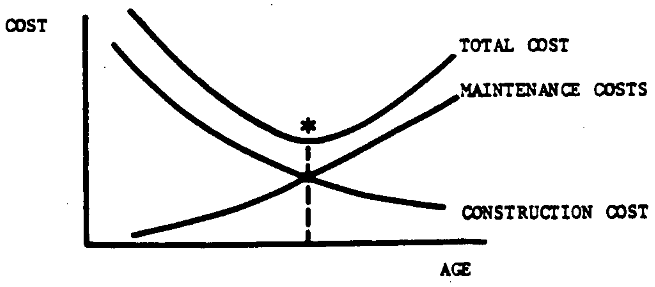
It should be emphasized that the discount rate used here to compute the annuity factor is not the same one used in Step 3 to find the present value. Rather, it is the cost of capital after an adjustment to eliminate the effect of inflation. An inflation-free discount rate is used here because the amount X should be expressed in constant dollars. If X were expressed in inflated dollars, the annualized cost of alternatives with different lives would be inflated different amounts, making comparisons meaningless.

Once each component of the steam of costs has been converted to an equivalent annual amount, the Cost Analyzer sums all of the components to find an equivalent annual cost for the construction and maintenance alternative under study. An annualized cost is computed for every possible life under the scenario being examined. The year in which this cost is at a minimum signifies the optimal life of a structure under that scenario. The annualized cost in this year can then be compared to the minimum annualized costs of other strategies.

Required Relationships

It should be clear from the preceding discussion that the Bridge Life Cycle Cost Analyzer does not automatically determine the effects of alternative construction/maintenance strategies. Rather, the Cost Analyzer is a tool for comparing the life cycle costs of alternative strategies *once the construction and maintenance cost (in current dollars) and corresponding life span of each alternative are known.*

The life cycle cost of a bridge is illustrated graphically below:



As age increases, the annualized capital or construction cost of a bridge (or any capital asset, for that matter) declines. That is, the capital cost function slopes downward and to the right because an increase in a bridge's life span increases the number of years over which its initial construction cost can be capitalized, thereby lowering the average annual cost of construction.

The cost of maintaining a bridge, on the other hand, increases with age. The operating cost function in the illustration above could just as easily be disaggregated into a number of individual curves representing the average cost of different maintenance activities performed during a bridge's life. In other words, it is simply the vertical summation of all maintenance costs incurred throughout a structure's life.

The total cost of building and maintaining a structure is the sum of the two cost functions. The optimal life of a bridge, from the standpoint of minimizing costs, corresponds to the low point on the u-shaped curve. Prior to this age, the full benefit of low maintenance costs has not been realized. After it, the costs of ownership steadily increase.

The total cost of owning and operating a bridge is determined by many factors, including structure type and the type, timing, and amount of maintenance work performed. Thus, different maintenance strategies will result in total cost functions of different shapes. For example, we would expect a bridge receiving no maintenance to require replacement (i.e., reach the low point on its total cost curve) much sooner than a structure subject to preventive maintenance program.

The total cost function illustrated represents the stream of costs incurred during a bridge's lifetime. The BLCCA converts this stream or cash flow into a single annualized cost. For a given maintenance strategy, the year in which this cost is lowest corresponds to the low point on the total cost curve and the optimal life of a structure under that scenario.

Thus, the Cost Analyzer enables bridge maintenance officials to, in essence, compare differently shaped cost functions resulting from different maintenance approaches. Before such comparisons can be made, however, the user must determine the shapes of these curves; that is, the user must identify the interrelationships betweeen structure type, maintenance activities, bridge life span, and bridge cost.

For example, reducing the frequency of, or eliminating altogether, a maintenance activity, such as painting, undoubtedly affects the cost of maintaining a bridge. It is by no means clear, however, how such a change in maintenance affects a maintenance activity such as painting because its marginal contribution (if any) to bridge condition and life span is influenced by so many different factors: how much painting is done; how often it is done; at what point(s) in a bridge's life it is done; and what kind of structure is being painted. This is precisely why it is so difficult to allocate bridge maintenance resources cost effectively—and yet, a clear understanding of these interrelationships is essential if scarce maintenance resources are to be used to maximum benefit.

The next section discusses the role of statistical analysis in defining these relationships and determining the costs and bridge life spans associated with different maintenance strategies. Once these relationships have been identified, the BLCCA may be used to compare competing alternatives.

STATISTICAL ANALYSES

The statistical analyses of NCDOT bridge maintenance and inspection data that were performed in testing this evaluation methodology illustrate the kinds of procedures that bridge maintenance officials must employ in order to compare the life-cycle costs of alternative maintenance strategies using the Bridge Life Cycle Cost Analyzer. Their principal objective was to generate the following data inputs to the BLCCA:

- Bridge construction cost.
- Expected bridge life as a function of maintenance intervention.
- Maintenance intervention costs.

However, these analyses cannot be considered definitive, either in terms of the approach used by Ernst & Whinney or its results, for both the types of analysis performed and the mathematical relationships identified reflect characteristics peculiar to the data examined, including NCDOT bridge construction and maintenance practices, North Carolina's climate and geography, the type of structure chosen for analysis, and the quality and quantity of data analyzed.

In other words, the results of the statistical analyses discussed in the following section are neither generalizable nor transferable to other states or regions. The fact that so many "local" factors influence the relationships between maintenance, bridge condition, and life expectancy dictates that any agency attempting to use this evaluation methodology develop procedures for defining these relationships that reflect local conditions, such as data availability. In short, it is impossible to delineate a definitive set of procedures that will automatically generate the data needed for comparing alternative maintenance strategies.

TEST APPLICATION OF BRIDGE LIFE CYCLE ANALYZER

To assess its practicality and usefulness to bridge maintenance officials, the evaluation methodology developed by Ernst & Whinney was tested using data from the North Carolina Department of Transportation (NCDOT). The principal objective of this test case was to use readily available data from a state department of transportation to empirically derive the data inputs to the Cost Analyzer (e.g., type, level, and timing of maintenance expenditures) needed to evaluate the effects of different maintenance approaches. This section describes the approach and results of the test application.

Data Acquisition and Preliminary Analysis

The State of North Carolina was chosen for testing the evaluation methodology for two reasons: the large number of bridges in the State and the willingness of officials in the NCDOT Bridge Maintenance Unit to provide the necessary data. North Carolina has 17,122 bridges; 16,645 of these are maintained by the State. North Carolina's bridge inventory is sufficiently large that a sizeable sample of structures of the same type could be analyzed, thereby controlling for the effects of structure type on maintenance requirements, condition, etc.

On the basis of contracts made during Phase I of NCHRP Project 14-6, arrangements were made with officials in the Bridge Maintenance Unit to obtain the inspection and maintenance expenditure data needed to test the evaluation methodology.

Data Sources

The data used to test the Cost Analyzer were obtained from two sources; Structure Inventory and Appraisal (SI&A) Files and NCDOT's annual Route and Bridge Reports.

The Surface Transportation Assistance Act of 1978 established National Bridge Inspection Standards (Title 23, Part 650 U.S.C.) requiring states to prepare and maintain a data base containing certain structure inventory and appraisal data. Under these standards, states are required to inspect all bridges at least biennially and to submit updated Structure Inventory and Appraisal records approximately once a year to the Federal Highway Administration for incorporation into the National Bridge Inventory.

Updated inspection data are submitted to FHWA on magnetic computer tapes. North Carolina completed its first inspection cycle in November 1980 and sent its first SI&A tape to FHWA in December 1980; the most recent update was submitted in May 1984. Although NCDOT inspected all federal-aid bridges prior to 1979, it had no formal inspection program for all bridges in the State and no computerized bridge maintenance data base until the end of that year. Thus the inspection data available for analysis covers a period of only 4½ years: from November 1979 when the first inspection cycle was begun to May 1984 when the most recent SI&A tape was sent to Washington.

SI&A data were chosen for analysis for two seasons: they include bridge condition ratings that are essential for determining the effects of alternative maintenance strategies; and they represent a systematic data collection effort in which all states participate. The use of widely available inspection data in the evaluation methodology significantly enhances its ease of implementation in other states.

The National Bridge Inspection Standards require states to submit for each structure the information shown in Exhibit C-4; this is a list of data elements comprising the National Bridge Inventory. Of course, states have the option of maintaining more detailed records and North Carolina's bridge maintenance data base currently contains some 80 additional items. However, this so-called "Expanded File" has only been implemented during the most recent inspection cycle, so data used in testing the Cost Analyzer were taken from the shorter Structure Inventory and Appraisal or "Federal" tapes, which are submitted to FHWA annually. Selected items from the data base which were examined during the test case will be described in greater detail below.

As can be seen from Exhibit C-4, the National Bridge Inventory and the SI&A records that update it contain no data on bridge maintenance expenditures, that is, data essential for quantifying the effects of different maintenance approaches on bridge life cycle cost. These data were obtained from NCDOT's Route and Bridge Reports for fiscal years (July 1–June 30) 1981–1984.

The Route and Bridge Report is a computerized data base containing records on all NCDOT expenditures by fiscal year. Expenditures on labor, equipment, and material are recorded by function code; function codes and descriptions of bridge maintenance activities are shown in Exhibit C-5. Route and Bridge Report records for each fiscal year are stored on a single magnetic tape. Of some 200,000 records on each fiscal year tape, approximately 30,000 are for expenditures on the entire North Carolina bridge inventory.

Selection of Data for Analysis

Structures Examined

One of the principal variables affecting bridge cost, life expectancy, and maintenance requirements is structure type. It would be unrealistic to expect mathematical functions that define the effects of maintenance on the condition and life expectancy of, say, timber bridges to also describe the effects of maintenance on concrete or steel structures. Accordingly, the test application of the evaluation methodology was limited to a single type of structure in order to factor out the effects of structure type on bridge condition and life expectancy.

Since a major goal of the test application was to statistically define the effects of various amounts of various types of maintenance on changes in bridge condition and life span, every effort was made to obtain the largest sample possible of bridges of the same structural type. The most common type of bridge in North Carolina is a steel stringer/multibeam or girder structure. Forty-two percent, or more than 7,100, of the State's bridges are of this type.

Of these 7,100 structures, slightly more than 60 percent were ultimately excluded from the analysis for a variety of reasons. For example, all draw spans and structures with missing data were excluded. In order to observe changes in condition over as long a period (4 years) as possible, structures that were not inspected in 1983 or 1984 were excluded. Finally, dual-span bridges, such as those usually found on interstate and other

EXHIBIT C-4.

STRUCTURE INVENTORY AND APPRAISAL DATA CONTAINED IN THE NATIONAL BRIDGE INVENTORY

State Code
Structure Number
Inventory Route
State Highway Department District
County (Parish)
City/Town Code
Features Intersected
Facility Carried by Structure
Location
Inventory Route, Min. Vertical Clearance
Milepoint
Road Section Number
Bridge Description
Defense Milepoint
Defense Section Length
Latitude
Longitude
Physical Vulnerability
Bypass, Detour Length
Toll
Custodian
Owner
Federal-Aid Project Number
Highway System
Administrative Jurisdiction
Functional Classification
Year Built
Lanes On and Under Structure
Average Daily Traffic
Year of Average Daily Traffic
Design Loan
Approach Roadway Width
Bridge Median
Skew
Structure Flared
Traffic Safety Features
Navigation Control
Navigation Vertical Clearance
Navigation Horizontal Clearance
Structure Open, Posted, Closed to Traffic
Type Service
Structure Type, Main
Structure Type, Approach Spans
Number of Spans in Main Unit
Number of Approach Spans
Total Horizontal Clearance
Length of Maximum Span
Structure Length
Curb or Sidewalk Widths
Bridge Roadway Width, Curb to Curb
Deck Width, Out to Out
Min. Vertical Clearance over Bridge Roadway
Min. Vertical Underclearance
Min. Lateral Underclearance on Right
Min. Lateral Underclearance on Left
Wearing Surface - Protective System
Deck
Superstructure
Substructure
Channel and Channel Protection
Culvert and Retaining Walls
Estimate Remaining Life
Operating Rating
Approach Roadway Alignment
Inventory Rating
Structural Condition
Deck Geometry
Underclearances, Vertical and Horizontal
Safe Load Capacity
Waterway Adequacy
Approach Alignment
Year Needed
Type of Service
Type of Work
Length of Improvement
Proposed Design Loading of Improvement
Proposed Roadway Width
Proposed Number of Lanes
Design ADT
Year of Estimated ADT
Year of Proposed Adjacent Roadway Improvements
Type of Proposed Adjacent Roadway Improvements
Cost of Improvements
P.E. Cost
Demolition Cost
Substructure Cost
Superstructure Cost
Date of Last Inspection
Sufficient Rating (Inserted by Edit/Update Program)

Source: Reference C-1 pp. 39-40

EXHIBIT C-5

FUNCTION CODES AND DESCRIPTIONS OF BRIDGE-RELATED EXPENDITURES RECORDED IN THE NCDOT ROUTE AND BRIDGE REPORT

FUNCTION CODE	DESCRIPTION OF FUNCTION
	BRIDGES
474	BRIDGE APPROACHES, SURFACING, OR PAVEMENT REPLACEMENT OR REPAIR Includes any backfill material, base course material, or bituminous surfacing required as a result of bridge replacement with another bridge, bituminous wearing surfaces on new bridges or that required because of maintenance or repairs to bridge floors; backfill material, or bituminous surfacing required as a result of substructure or superstructure maintenance or repair, including that required because of scouring.
475	BRIDGE REPLACEMENT WITH ANOTHER BRIDGE Removal and replacement of an existing bridge with a new bridge.
476	BRIDGE REPLACEMENT WITH PIPE OR CULVERT Removal and replacement of an existing bridge with a pipe or reinforced concrete box culvert. Includes any backfill material, base course, or bituminous surfacing required.
477*	SPOT MAINTENANCE PAINTING OF STRUCTURAL STEEL Spot cleaning and painting of structural steel bridge superstructure components; or
	COMPLETE MAINTENANCE PAINTING OF STRUCTURAL STEEL Complete cleaning and painting of structural steel bridge superstructure components.
478	MAINTENANCE AND REPAIRS TO CONCRETE BRIDGE FLOORS Removal of deteriorated concrete and repair of concrete bridge floors. Also includes the application of epoxy seals, crack sealing.
479	REPAIRS TO TIMBER BRIDGE FLOORS Spit repair of timber bridge floors and additional nailing and bolting to tighten.
480	REPAIRS TO STEEL PLANK BRIDGE FLOORS Partial replacement of steel bridge floors and repair to connection between floor and supporting beams by placing additional studs, bolts, welding, etc.
481	MAINTENANCE OR REPAIRS TO TIMBER BRIDGE HANDRAILS Maintenance or repairs to timber bridge handrails, posts, post blocks, and wheel guards due to poor condition. Includes painting and placing asphalt on timber wheel guard and post block.
482	MAINTENANCE OR REPAIRS TO CONCRETE BRIDGE HANDRAILS Maintenance or repairs to concrete bridge handrails, posts, and post brackets due to poor condition. Includes repair with concrete and painting with a reflective coating.
483	MAINTENANCE OR REPAIRS TO ALUMINUM BRIDGE HANDRAILS AND CONCRETE PARAPETS Maintenance or repairs to aluminum bridge handrails or concrete parapet due to poor condition. Includes repair parapet with concrete, crack sealing, etc.
484	FENDER SYSTEM Construction, maintenance, or replacement of fender systems including piles, dolphins, wales, bracing, etc. Includes placement of a cathodic corrosion protection system on steel fender systems.
485	PEDESTRIAN BRIDGES Initial installation or maintenance of pedestrian bridges.
486	BRIDGE INSPECTION
487	MAINTENANCE OR REPAIRS TO STEEL BRIDGE HANDRAILS Maintenance or repairs to steel bridge handrails, posts, post brackets, and steel curbs. Includes maintenance painting, replacement of bolts, etc.

Source: Reference C-2 Attachment W.

*Spot painting and complete painting were formerly coded as separate activities.

EXHIBIT C-5 (Cont.)

FUNCTION CODE	DESCRIPTION OF FUNCTION
488	MAINTENANCE OF STEEL EXPANSION JOINT DEVICES Miscellaneous repairs to steel deck expansion joints such as grouting anchors and fabricating and welding additional anchors. Includes steel plate and finger-type expansion joints.
489	DRAW SPANS Installation of electrical or mechanical equipment that forms a part of movable-span bridges, and includes housing, gates, flashing signals, and traffic safety devices, and the maintenance and repair of same and the maintenance, repair or service of any stationary equipment. Also includes salary of drawbridge operators, heat, power, lights, and telephone.
490	MAINTENANCE OF STANDARD DECK EXPANSION JOINTS Miscellaneous repairs to standard 1"± wide deck expansion joints constructed with expansion joint material and sealed with asphalt. Includes removing existing seal, cleaning, and resealing.
491	MAINTENANCE OF MISCELLANEOUS DECK EXPANSION JOINTS Miscellaneous repair to various other prefabricated expansion joint devices.
492	GENERAL MAINTENANCE OR REPLACEMENT OF BRIDGE SUPERSTRUCTURE Miscellaneous repairs or complete replacement of a bridge superstructure. Complete replacement of a superstructure element such as floor, handrail, etc. Includes repairs to diaphragms, concrete girder ends, bearings, placing additional beams or joists, replacing truss members, etc.
493	MAINTENANCE OR REPLACEMENT OF TIMBER SUBSTRUCTURE Repairs to timber piles such as placing concrete or polyethylene jackets, driving additional piles, treatment of piles and bulkheads with asphalt, and replacement of substructure elements such as caps, posts, sills, bracing, bulkhead, tiebacks, etc.
494	MAINTENANCE OR REPLACEMENT OF PRESTRESSED CONCRETE PILE SUBSTRUCTURE Repairs to prestressed concrete piles such as patching, jacketing with concrete, crack grouting, placing protective coating, and driving additional piles.
495	MAINTENANCE OR REPLACEMENT OF PRECAST CONCRETE PILE SUBSTRUCTURE Repairs to precast concrete piles such as patching, jacketing with concrete, crack grouting, placing cathodic corrosion protection system, placing protective coating, guniting, and driving additional piles.
496	MAINTENANCE OR REPLACEMENT OF STEEL PILE SUBSTRUCTURE Repairs to steel piles such as jacketing with concrete, placing cathodic corrosion protection system, repairs to steel bracing, and driving additional piles. Includes maintenance painting.
497	MAINTENANCE OR REPLACEMENT OF CONCRETE PIERS AND ABUTMENTS Repairs to concrete piers and abutments such as patching, crack grouting, etc. Includes replacement due to poor condition or severe settlement.
498	BRIDGE DAMAGES DUE TO ACCIDENT OR VANDALISM Damages to any parts of a bridge or fender system caused by highway or waterway traffic and including vandalism.
499	MAINTENANCE OF SLOPES AND SHORE PROTECTION DEVICES Repairs to slope and shore protection devices including concrete and stone riprap, timber, steel and concrete sheeting. Also includes placing additional shore protection devices such as driving sheeting at end bents for scour protection.
580	SWEEPING OR WASHING OF ROADWAYS OR BRIDGES EXCLUDING THAT REQUIRED FOR THE REMOVAL OF DE-ICING CHEMICALS OR ABRASIVES Includes curb cutting or trimming to remove grass growth by either manual or mechanical means. Includes disposal of sand or other debris.

primary roads, had to be excluded from the analysis because of the difficulty in matching inspection and maintenance expenditure records for these structures. The final sample size of 2,686 structures represents approximately 38 percent of all steel stringer/multibeam or girder bridges in North Carolina and approximately 15 percent of the State's entire bridge inventory.

Variables Examined

The principal variables examined in the test application of the evaluation methodology are shown in Exhibit C-6. Historical data on bridge maintenance expenditures were taken from NCDOT's Route and Bridge Reports; all other data are from the Structure Inventory and Appraisal Files.

The statistical analysis performed as part of the test application of the evaluation methodology were intended (1) to determine the effects of different maintenance activities on changes in bridge condition and life expectancy, and (2) to derive data inputs to the Bridge Life Cycle Cost Analyzer program using the mathematical relationships identified. The measures of bridge condition used here were condition ratings assigned to each structure during biennial inspections.

SI&A records contain *condition* ratings, where appropriate, for deck, superstructure, substructure, channel and channel protection, culvert and retaining walls, and approach roadway. Condition ratings, interpretations of which are shown in Exhibit C-7, are measures of a structure's *physical* condition only; they tell us nothing about a bridge's performance as it relates to the highway system of which it is a part, such as its load-carrying capacity. As such, a combination of these ratings is better suited to an analysis of the cost effectiveness of various maintenance activities than are some of the *appraisal* ratings found in SI&A records, which, although they apply to an entire structure, incorporate assessments of such factors as load-carrying capacity and essentiality for public use.

An initial examination of the maintenance expenditure categories used in NCDOT Route and Bridge Reports (Exhibit C-5) suggested that it would be difficult to determine the effects of a given maintenance approach on a structure's "sub" (e.g., superstructure, deck) condition ratings. Accordingly, a measure of overall bridge condition was created by summing the deck, superstructure, and substructure ratings for each bridge examined. This rating was deemed a better indicator of a structure's overall physical condition than either the Structural Condition Rating or the Sufficiency Rating found in all SI&A records. Since condition ratings are based on a scale of 0 to 9, the composite bridge condition rating used in the test application could range from 0 to 27. Ultimately, however, there were insufficient data to examine a full-fledge, multiactivity maintenance approach in the test application, and superstructure condition ratings, rather than this composite measure of overall condition, were used in examining the effects of a single maintenance activity, painting.

Most of the other variables listed in Exhibit C-5 are self-explanatory. All dollar amounts spent on bridge maintenance in fiscal years 1981–1984 and estimated replacement cost (in 1984) were converted to unit costs by dividing them by deck area in order to factor out the effects of structure size. Of 27 bridge maintenance categories in the Route and Bridge Report data base, only 12 were included in the analysis. Maintenance expenditures that were deemed to have little or no impact on

EXHIBIT C-6

PRINCIPAL VARIABLES EXAMINED IN TEST APPLICATION
OF THE EVALUATION METHODOLOGY

- Age
- Average Daily Traffic (ADT)
- Deck Area
- Deck, Superstructure, Substructure, and Bridge (overall) Condition Ratings
- Change in Condition Ratings, 1980-84
- Estimated Remaining Life
- Change in Estimated Remaining Life, 1980-84
- Expenditures on Maintenance FY 81-84 for Activities 474, 475, 476, 477, 478, 479, 490, 492, 493, 494, 497, 580 (cents per square foot of deck)*
- Replacement Cost (cents per square foot of deck)

* The following expenditure categories were excluded: 481-483, 487 (Repairs to Handrails); 485 (Maintenance of Pedestrian Bridges); 486 (Bridge Inspection); 489 (Repairs to Draw Spans); 498 (Repairs due to Accidents or Vandalism); 499 (Maintenance of Slopes and Shore Protection Devices). There were no expenditures in FY 81-84 in the remaining bridge-related maintenance categories (480, 484, 488, 491, 495, 496). See Exhibit C-5 above for more detailed descriptions of bridge maintenance categories.

EXHIBIT C-7

INTERPRETATION OF CONDITION RATINGS IN STRUCTURE
INVENTORY AND APPRAISAL RECORDS

Rating	Interpretation
9	New Condition
8	Good condition--no repairs needed
7	Generally good condition--potential exists for minor maintenance
6	Fair condition--potential exists for major maintenance
5	Generally fair condition--potential exists for minor rehabilitation
4	Marginal condition--potential exists for major rehabilitation
3	Poor condition--repair or rehabilitation required immediately
2	Critical condition--the need for repair or rehabilitation is urgent; facility should be closed until the indicated repair is completed
1	Critical condition--facility is closed study should determine the feasibility of repair
0	Critical condition--facility is closed and is beyond repair

Source: Reference C-3

structure condition (e.g., for repairs to handrails), or which are unrelated to normal wear and tear (e.g., for repair due to accidents or vandalism) were excluded. No expenditures were reported by NCDOT under six maintenance categories during the 4 years examined.

Limitations of the Data

It has already been pointed out that the approach to and results of the statistical analyses performed in testing the evaluation methodology are neither generalizable nor transferable to other states. Nevertheless, the principal limitations of the NCDOT data (from the standpoint of comparing the costs associated with different maintenance strategies) should be identified in order to fully understand why certain analyses were (or were not) performed; what their results do and do not tell one about the effects of maintenance; and on what basis the recommendations for methodology refinement and data base development were made. It should be emphasized, however, that these limitations are by no means unique to North Carolina.

Availability

Since one of the principal objectives of the evaluation methodology, indeed of NCHRP Project 14-6, is to determine the effects of maintenance on bridge life expectancy (and, hence, life-cycle cost), perhaps the most serious limitation of the data is the lack of information on bridge condition prior to November 1979 (when inspections mandated by the National Bridge Inspection Standards began), and on bridge maintenance expenditures prior to fiscal year 1981 (that is, prior to July 1980).

Because most bridges in North Carolina were not inspected for the first time until 1980, it is currently impossible to observe changes in bridge condition over a period of more than 3½ to 4 years. As will be shown below, this lack of longitudinal data significantly hampers one's ability to accurately assess the effects of maintenance performed at different points in a bridge's life by preventing one from accounting for changes in design and construction practices over time and for maintenance performed prior to fiscal year 1980—both of which influenced changes in bridge condition between 1980 and 1984. In other words, cross-sectional data alone do not provide a complete and accurate picture of the effects on bridge condition and life expectancy of performing a given maintenance activity at different points in a bridge's life.

Even if one wishes to concentrate only on maintenance performed since bridge inspections began in 1979, the data are still incomplete. Only the three most recent NCDOT Route and Bridge Reports (that is, for the three most recent fiscal years) are maintained on magnetic tape. Expenditure data for FY 1981 were manually recorded from a computer printout into the microcomputer data base on which analyses were performed. However, data on expenditures prior to fiscal year 1981 and, hence, from November 1979, when bridge inspections began, until July 1980, are no longer available.

Although it appears unlikely that the lack of expenditure data for these 8 months would have any significant effect on the mathematical relationships discussed below, because only 342, or 12.7 percent, of the 2,686 bridges in the project's sample experienced any maintenance during the 4 fiscal years examined, it is clearly preferable to have complete expenditure data for the period being analyzed. Unfortunately, these data are also incomplete for another reason: in discussing the results of the test application with NCDOT bridge maintenance officials, it was discovered that bridge maintenance work performed by outside contractors is not included in the Route and Bridge Reports.

Over the last 3 years or so, approximately 2.6 million dollars' worth of bridge painting was performed by contractors on the State's entire inventory. Although almost all of this amount was spent on primary bridges that were excluded from the test application (as explained above), it is likely that some painting expenditures are unaccounted for in the sample examined in the project. While it should be reiterated that the results of the statistical analyses performed in testing the evaluation methodology are not definitive, such an omission may have affected the relationship between painting and changes in bridge condition and life expectancy identified below.

The omission of contract maintenance expenditures highlights a major limitation of NCDOT's bridge maintenance data bases from the standpoint of analyzing the effects of maintenance: the practice of maintaining inspection and expenditure data in three separate data bases. The difficulty of merging records from the SI&A Files and Route and Bridge Reports was compounded by the fact that, until recently, the bridge identification numbers used in the former data base were not identical to those used in the latter. In particular, this prevented the inclusion of dual-span bridges (usually found on interstate and other primary roads) in the analysis because of the inability to match records for these structures from the two files.

From the standpoint of using the Bridge Life Cycle Cost Analyzer, another limitation of the data is the omission of initial construction cost from NCDOT's computerized data bases. The capital cost used to generate sample BLCCA reports is the replacement cost found in all SI&A records. The principal drawback of using this figure is that it frequently represents the cost of building a better bridge (e.g., in terms of approach, alignment, or structure type) than the current structure, and thus tends to overstate the initial construction cost of the current structure. On the other hand, the mean replacement cost, for the 2,686 structures examined, of $375,000 is fairly consistent with average replacement costs found in other states (see, for example, Ref. C-4, p.1)

Accuracy

Although a small number of bridges were eliminated from the final sample of structures analyzed in the test application because of missing data, the data obtained from NCDOT generally appeared to be accurate. However, two problems in this regard were encountered. First, of 2,344 structures in the sample that did not receive any maintenance in FY 1981–1984, 716, or 31 percent, experienced an *improvement* in overall condition between 1980 and 1984. Needless to say, it is unrealistic to suggest that bridge condition can improve over a 4-year period without any maintenance being performed.

This anomaly can perhaps be explained, in part, by the omission of contract painting expenditures noted above. However, it is more likely because the first cycle of bridge inspections (in 1979–1980) was performed by nine consulting firms, the second by seven outside firms, and the most recent by NCDOT inspectors. Such changes in bridge inspection personnel, which also have been made by other states that formerly employed consulting firms, undoubtedly resulted in differing perceptions of bridge conditions that may have caused many initial ratings to be revised upward in more recent inspections.

Regardless of the explanation, the fact that almost a third of the unmaintained structures was given higher condition ratings in 1984 than in 1980 highlights two important points. First, condition ratings should not be viewed as perfect measures of a structure's condition. Second, in as much as condition ratings are subjective assessments made by trained inspectors of a structure's condition, their accuracy is extremely susceptible to changes in inspection policies and procedures—such as are likely to occur if an agency switches from contractor to in-house inspectors. There can be little doubt that the transition from nine independent consulting firms to NCDOT regional offices has had some effect on the inspection data used in testing the evaluation methodology.

The second accuracy-related problem pertains to the calculation of bridge age. As the list of National Bridge Inventory items in Exhibit C-4 indicates, the year in which a structure is built, rather than actual structure age, is recorded in the SI&A Files. Bridge age was determined, for the purposes of the test application, simply by subtracting the value of Item 27, Year Built, from 1984.

However, Item 27 frequently consists of two 2-digit numbers: the year of initial construction and the year in which a bridge was reconstructed. For reconstructed bridges, the date of *reconstruction* was used to determine bridge age. Bridge Maintenance Unit officials have indicated that structures are reported to have been reconstructed when (1) a structure has been widened to change bridge geometrics; (2) significant structural work has been done to change live load capacity, or (3) only part of a bridge, such as the deck, has been reconstructed. As a result, the age of some of the structures examined in the test application has undoubtedly been understated.

Informational Value

From the standpoint of determining the cost effectiveness of specific bridge maintenance activities, such as spot painting or pavement patching, a principal limitation of the NCDOT expenditure data is the relatively broad categories (shown in Exhibit C-5) under which maintenance expenditures are recorded. For instance, it is impossible to determine, short of manually reviewing work orders placed in a given structure's file folder, whether an expenditure charged to function code 478, Maintenance and Repairs to Concrete Bridge Floors, refers to removal and replacement of deteriorated concrete, application of epoxy seals, crack sealing, or some other activity. Consequently, it is impossible to determine the effects on bridge condition and life expectancy (and, hence, life-cycle cost) of, say, patching in the fifth year of a structure's life versus complete resurfacing in the eighth year. It should be pointed out, however, that NCDOT uses far more bridge maintenance expenditure categories (27) than the average for most other states of around 10 categories.

Another problem pertains to maintenance performed in response to "prompt-action" notices. For instance, if a bridge whose superstructure condition rating is downgraded from a 4 in 1982 to a 3 in 1984 receives maintenance in response to a prompt action notice between the date it was inspected in 1984 and the date that the 1984 SI&A tape is sent to Washington, its superstructure condition may well be upgraded to a 4 before the tape is sent to Washington. As a result, a large amount of money will have been spent on critical repairs and yet not be reflected in the structure's condition rating, which shows up as a 4 in both 1982 and 1984.

A final drawback of the data arises from the relatively small scale used for assigning condition ratings. Because the scale consists of only 10 points, a one-point change in a given condition rating should represent a 10 percent improvement or decline in condition. However, many maintenance activities may result in an improvement in structure condition which, although perceptible to a bridge inspector, does not merit a one-point, 10 percent change in condition rating. In short, this rating scale (which, incidentally, is used by all 50 states for rating bridges) is not precise enough to reveal the effects of any and all maintenance activities. This further compounds the difficulty of determining the cost effectiveness of alternative maintenance activities and approaches.

Model for Generating BLCCA Inputs

The Bridge Life Cycle Cost Analyzer requires the following inputs:

- Bridge construction cost
- Expected bridge life as a function of maintenance intervention
- Maintenance intervention cost

To generate these inputs from the North Carolina data base, a model consisting of various statistical relationships was constructed. These relationships and the manner in which they were used to construct alternative maintenance scenarios are shown in Exhibit C-8.

The user begins by selecting the current age of bridge which is the focus of the analysis. For example, one would select age zero to construct a maintenance scenario for newly constructed bridges. Alternatively, one could select age 20 to develop a maintenance scenario for bridges that currently are 20 years old.

The second step uses a formula derived from the SI&A data base to estimate the initial condition of the bridge given its age. The estimate is the predicted condition of bridges for the specified age.

The third step presents the choice between maintenance interventions and no maintenance intervention in the first period of analysis. (All maintenance interventions and changes in bridge condition are calculated for periods of 4 years, reflecting the period for which NCDOT inspection and maintenance data were available.) The choice between maintenance and no maintenance determines the formula used to estimate the change in the condition of the bridge which will occur during the period. The formulas are derived from the SI&A data base, and they provide an estimate of change in condition over a 4-year period as a function of beginning condition. Thus, the fourth step in the model is to estimate the change in condition from the initial condition, given a maintenance or no maintenance choice. If maintenance intervention is selected, the cost of performing that maintenance also is estimated in Step 4. The cost of the intervention is estimated as a function of bridge condition at the time the intervention occurs and is derived from the SI&A data base.

Step 5 is the calculation of the new bridge condition, the condition of the bridge at the end of the period. It simply equals the initial condition less the estimated change in condition. The sixth step records the fact that the bridge has aged during the period. As previously noted, each period is 4 years long so by the end of the first period, bridge age equals initial age plus four.

Step 7 is a check point: Has the threshold condition been attained? The threshold condition is that condition which marks the end of the bridge's useful life. When this threshold is reached, the bridge must be reconstructed or replaced. The threshold condition used in this model for a single bridge component (i.e., superstructure, substructure, or deck) is 5.0. Although this rating is relatively high, given the definitions provided earlier in Exhibit C-5, it appears to be the threshold condition used by NCDOT's Bridge Maintenance Unit. Very few of the bridges in the sample (2.3 percent) have ratings less than 5.

If the threshold condition is attained, the maintenance scenario is complete. Data generated by the model at this point include when maintenance interventions will occur, how much they will cost, and the age of the bridge when the threshold condition is reached. These become inputs to the BLCCA along with the cost to construct the bridge. As discussed earlier, this cost in the model is the average cost to replace a bridge given its threshold condition, as determined from the SI&A data base. Because the data base does not include original construction cost, the cost to replace is used as a surrogate for construction cost in the case of bridges age one and more.

If the threshold condition is not attained at the end of the first period, the cycle is iterated. One is again given the choice of maintenance intervention or no maintenance intervention; the change in condition is calculated; the new condition now at the end of the second period is calculated as is the new age; and the threshold question is again posed. This cycle is repeated until the threshold condition is attained (that is, until a structure has reached the end of its useful life under the maintenance scenario being examined) and data for the BLCCA are produced.

Application of the Model

To illustrate the model, painting was chosen as the mainte-

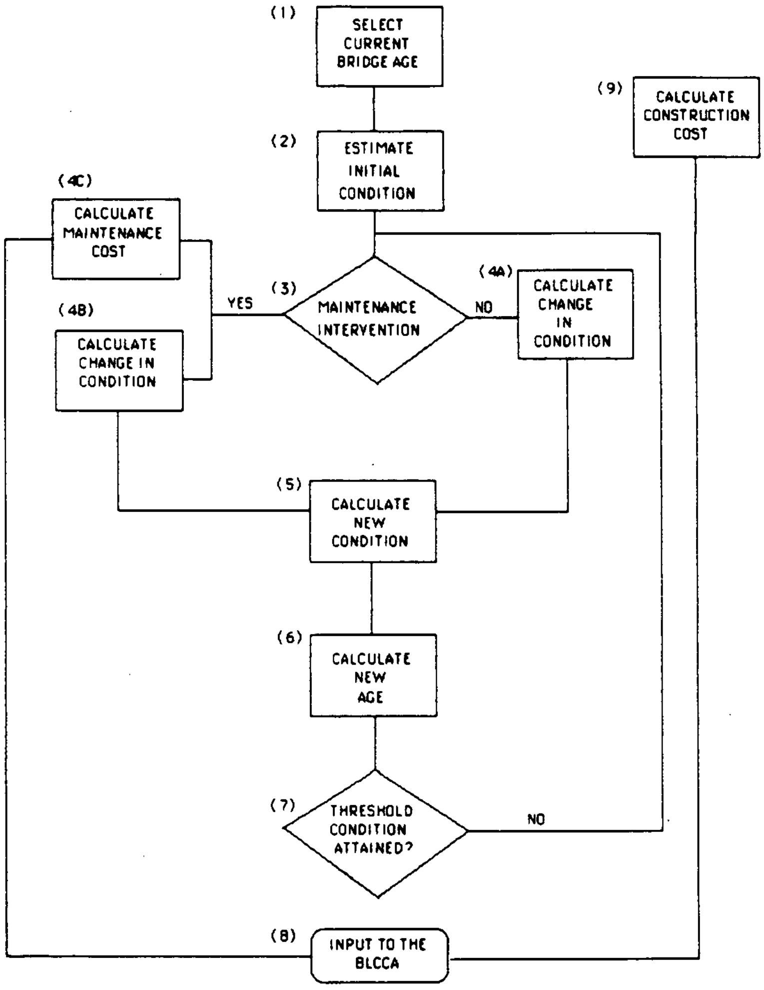


Exhibit C-8. Model for generating BLCCA data requirements.

nance intervention activity. There were several reasons for this choice. Painting is a preventive maintenance activity performed by all bridge maintenance units and, consequently, is of universal interest. More significant in this study, is the fact that painting was one of the few maintenance activities (the others being repair to timber substructures and repair to timber decks) with a large enough number of cases to evaluate statistically. The number of bridges on which maintenance was performed during the analysis period is shown, by maintenance activity, in Exhibit C-9.

The focus on painting also required use of the superstructure condition rating as the basis for estimating change in bridge condition over time, because the superstructure is the bridge element affected by maintenance painting.

These two aspects of the model illustration (single maintenance activity and single condition focus) point up two constraints to using the SI&A and Route and Bridge Report data bases. First, there are only sufficient observations to examine one maintenance activity at a time. Trying to examine alternative combinations of maintenance activities will tend to be frustrated by a lack of sufficient observations to statistically establish life expectancy (i.e., the point at which the threshold condition is attained) under different maintenance approaches. Because individual maintenance activities usually affect only one bridge component (superstructure, substructure, or deck), the examination of maintenance activities was pursued on this basis.

The Estimating Formulas

The formulas derived from the SI&A and Route and Bridge Report data bases are used in steps 2, 4A, 4B, 4C, and 9 of the model shown in Exhibit C-8. These formulas are presented in Exhibit C-10 and further described below.

The first formula in Exhibit C-10 is used to estimate the initial condition of a bridge given its age at the start of the analysis. The data base used to determine the relationship shown was the entire set of bridges in the sample (2,686). The equation is a simple linear regression with a correlation coefficient of 0.34. (Other formulations of current condition including multiple regression equations with independent variables such as ADT and deck area were tried without finding any statistically significant relationships.)

The second formula is used to compute the estimated change in superstructure condition if no maintenance is performed during a given period. The period of time is 4 years because the estimated change is derived from the change in condition from 1980 to 1984 of all bridges in the sample that received no maintenance intervention. Also the sample size was reduced to exclude all bridges that received no maintenance during the period but *improved* in condition; this outcome was believed to be unreasonable and attributable to other factors. Positive changes occurred apparently because some of these bridges in fact received maintenance during the period which was not recorded in the Route and Bridge File (i.e., the contract maintenance problem discussed earlier). Another likely cause of positive changes was the change from outside inspectors to in-house inspectors and the differences in opinions about condition rendered by them.

The formula for determining the estimated change in condition is based on the condition of the superstructure at the beginning of the period. Analysis revealed that this independent

EXHIBIT C-9

FREQUENCY OF MAINTENANCE INTERVENTION
BY MAINTENANCE FUNCTION
1980-1984

MAINTENANCE FUNCTION NO. 1/	NUMBER OF BRIDGES ON WHICH MAINTENANCE WAS PERFORMED
474	4
475	6
476	14
477	125
478	10
479	41
490	19
492	79
493	119
494	3
497	8
580	8
TOTAL	342 2/

1/ Refer to Exhibit C-2 for the definition of each function.

2/ Total does not equal the sum of all activities because more than one maintenance function was performed on some bridges.

EXHIBIT C-10

MODEL USED TO ESTIMATE BRIDGE LIFE CYCLE
COST ANALYZER INPUTS

DEPENDENT VARIABLE	INDEPENDENT VARIABLE	ESTIMATING FORMULA	KEY STATISTICS			
			n	r 2	t	significance
(1) Initial condition	Current age	y=7.462 - 0.039x	2686	.34	18.9	.000
(2) Change in condition over four years with no maintenance	Initial condition	See Table 1	1628	NA	NA	NA
(3) Change in condition over four years with painting	Initial condition	See Table 1	90	NA	NA	NA
(4) Cost to paint	Initial condition	y=23.838 - 2.039x	90	.18	1.8	.077

variable provides the strongest basis for estimating change in condition (as opposed, for example, to age at the beginning of the period).

Also, the function used to estimate change is a step function as opposed to a continuous function. The estimated change in condition is the mean change in condition observed for bridges grouped by initial condition. This approach was used to avoid placing undue weight on initial conditions that occurred more frequently in the sample than others.

The third formula shown in Exhibit C-10 is used to estimate the change in superstructure condition if the bridge is painted. As with the no maintenance case, the change is that estimated to occur over the 4-year period during which the painting was done. The estimated change in condition is based on the 90 bridges from the sample that had no other maintenance intervention than painting during this period. That is, of the 125 bridges in the sample that were painted, 35 also received other maintenance treatment. To isolate the effects of painting, these 35 bridges were excluded from the analysis.

As with the formula for estimating change in condition with no maintenance, this formula is a step function indicating the mean change in condition for bridges with a given initial condition.

The final calculation, bridge construction cost, is a constant ($378,000) which, as noted earlier, equals the average 1984 replacement cost for all bridges.

Illustrative Maintenance Scenarios

Using the model and formulas specified above, various maintenance scenarios were developed to illustrate the proposed methodology. These scenarios are shown in Exhibit C-11 through C-16.

The first exhibit shows a no maintenance scenario for a new bridge, the results of performing no maintenance throughout a bridge's life. The computations indicate that this maintenance approach would result in an expected life of about 78 years. Clearly, this is an unrealistic outcome; a bridge which received no maintenance during its life would not be expected to last this long. A second unrealistic result of the scenario is the declining magnitude of the change in condition. On the contrary, one would expect the change in condition to increase as the cumulative effect of years of no maintenance took its toll on a bridge's superstructure.

The reason for these outcomes is the limited longitudinal data available for analysis. Predicted change in condition is based on the actual change which occurred in a 4-year period and the combination of these 4-year changes, by initial condition, to construct a deterioration function over time. A more accurate indication of the cumulative effect of no maintenance would be available with a data base spanning a longer time frame. The problem encountered with the limited longitudinal data increases with bridge age. The decreasing magnitude of change with bridge age appears to reflect the effect of maintenance performed before 1980 which is the first year of our analysis period.

Despite these problems, comparison to the other maintenance scenarios indicates that the relative, if not the absolute, outcomes are logical. Exhibit C-12 shows a no maintenance profile for a bridge beginning in the bridge's 20th year. Given the source of the data for estimating initial condition, this scenario includes the normal maintenance program of NCDOT through year 20. Comparing the estimated superstructure condition in year 20 of scenario 1 (no maintenance in the first 20 years) and this scenario shows that the bridge which was maintained has a 5

EXHIBIT C-11
MAINTENANCE SCENARIO 1

INITIAL AGE = 0 NO MAINTENANCE

AGE	CHANGE IN CONDITION	NEW CONDITION	PAINTING EXPENDITURES
0	N/A	7.4620	N/A
4	(0.2240)	7.2380	
8	(0.2240)	7.0140	
12	(0.2240)	6.7900	
16	(0.2240)	6.5660	
20	(0.2240)	6.3420	
24	(0.1170)	6.2250	
28	(0.1170)	6.1080	
32	(0.1170)	5.9910	
36	(0.1170)	5.8740	
40	(0.1170)	5.7570	
44	(0.1170)	5.6400	
48	(0.1170)	5.5230	
52	(0.1170)	5.4060	
56	(0.0630)	5.3430	
60	(0.0630)	5.2800	
64	(0.0630)	5.2170	
68	(0.0630)	5.1540	
72	(0.0630)	5.0910	
76	(0.0630)	5.0280	
80	(0.0630)	4.9650	

EXHIBIT C-12
MAINTENANCE SCENARIO 2

INITIAL AGE = 20 NO MAINTENANCE

AGE	CHANGE IN CONDITION	NEW CONDITION	PAINTING EXPENDITURES
20	N/A	6.6820	N/A
24	(02240)	6.4580	
28	(0.1170)	6.3410	
32	(0.1170)	6.2240	
36	(0.1170)	6.1070	
40	(0.1170)	5.9900	
44	(0.1170)	5.8730	
48	(0.1170)	5.7560	
52	(0.1170)	5.6390	
56	(0.1170)	5.5220	
60	(0.1170)	5.4050	
64	(0.0630)	5.3420	
68	(0.0630)	5.2790	
72	(0.0630)	5.2160	
76	(0.0630)	5.1530	
80	(0.0630)	5.0900	
84	(0.0630)	5.0270	
88	(0.0630)	4.9640	

percent higher condition rating. This bridge also has an estimated life expectancy 8 years to 10 percent longer than that of a bridge under scenario 1.

Exhibits C-13 and C-14 present two scenarios in which painting is performed. The first scenario, with painting about every 16 years, approximates the current NCDOT policy for the type of bridge examined in this analysis. The second scenario assumes a less frequent painting cycle. Both scenarios indicate that painting extends bridge life beyond that of the no maintenance approach: by 67 percent under the 16-year painting cycle, and by 41 percent under the less frequent painting cycle.

A Second Perspective

Given the problem associated with inadequate longitudinal data, a second approach to examining the effects of alternative maintenance programs was taken. Rather than compare painting with no maintenance, scenarios were developed to (1) reflect continuation of the recent maintenance program, and (2) reflect continuation of the current maintenance program with more frequent painting.

The first scenario was developed by assuming that the historical decline in superstructure condition rating (−0.156 over 4 years) is a reasonable rate of deterioration given continuation of the current maintenance program. The average maintenance expenditure per bridge which corresponds to this program is about $1,100 (this figure is a very rough approximation of the amount spent during the 1980–1984 period).

The average painting cycle in North Carolina for the type of bridge examined in this analysis is 16 years. This cycle, then, is implicitly part of the historical maintenance program. In the second scenario, it is assumed that the painting cycle is 8 years. Painting in years 8, 24, and 40 was added to the first scenario to derive the second one. The change in superstructure condition associated with the additional painting was estimated as before, using the stepwise function shown in Exhibit C-10.

The characteristics of these two profiles are shown in Exhibits C-15 and C-16. According to the first scenario (scenario 5) the expected life of a bridge under a continuation of the traditional NCDOT maintenance program is about 62 years. This compares to a life of about 82 years when the traditional program is enhanced with additional painting in years 8, 24, and 40. An increase of 32 percent in expected bridge life is achieved.

These estimates of expected life are much more realistic than those estimated earlier (scenarios 1 to 4) and indicate the order of magnitude of the problem with having limited longitudinal data. Until additional longitudinal data can be obtained to better determine the cumulative effects of no maintenance, the data base and model proposed here will have to be applied to analyses of marginal changes from current maintenance practice as opposed to major changes.

Life Cycle Cost Results

Of course, the analyses presented above do not determine whether one maintenance scenario is preferable to another. To answer the question of whether the extended life of the bridge is worth the additional maintenance costs incurred, the life-cycle costs of each scenario need to be calculated and compared using the Bridge Life Cycle Cost Analyzer.

EXHIBIT C-13
MAINTENANCE SCENARIO 3

INITIAL AGE = 0 PAINTING IN YEARS 14,30,46,AND 62

AGE	CHANGE IN CONDITION	NEW CONDITION	PAINTING EXPENDITURES
0	N/A	7.4620	N/A
4	(0.2240)	7.2380	
8	(0.2240)	7.0140	
12	(0.2240)	6.7900	1,900
16	(0.0650)	6.7250	
20	(0.2240)	6.5010	
24	(0.2240)	6.2770	
28	(0.1170)	6.1600	2,150
32	0.4290	6.5890	
36	(0.2240)	6.3650	
40	(0.1170)	6.2480	
44	(0.1170)	6.1310	2,150
48	0.4290	6.5600	
52	(0.2240)	6.3360	
56	(0.1170)	6.2190	
60	(0.1170)	6.1020	2,175
64	0.4290	6.5310	
68	(0.2240)	6.3070	
72	(0.1170)	6.1900	
76	(0.1170)	6.0730	
80	(0.1170)	5.9560	
84	(0.1170)	5.8390	
88	(0.1170)	5.7220	
92	(0.1170)	5.6050	
96	(0.0630)	5.5420	
100	(0.0630)	5.4790	
104	(0.0630)	5.4160	
108	(0.0630)	5.3530	
112	(0.0630)	5.2900	
116	(0.0630)	5.2270	
120	(0.0630)	5.1640	
124	(0.0630)	5.1010	
128	(0.0630)	5.0380	
132	(0.0630)	4.9750	

EXHIBIT C-14
MAINTENANCE SCENARIO 4

INITIAL AGE = 0 PAINTING IN YEARS 22 AND 46

AGE	CHANGE IN CONDITION	NEW CONDITION	PAINTING EXPENDITURES
0	N/A	7.4620	N/A
4	(0.2240)	7.2380	
8	(0.2240)	7.0140	
12	(0.2240)	6.7900	2075
16	(0.2240)	6.5660	
20	(0.2240)	6.3420	
24	(0.4290)	6.7710	
28	(0.2240)	6.5470	
32	(0.2240)	6.3230	
36	(0.1170)	6.2060	
40	(0.1170)	6.0890	
44	(0.1170)	5.9720	2,125
48	0.4290	6.4010	
52	(0.1170)	6.2840	
56	(0.1170)	6.1670	
60	(0.1170)	6.0500	2,175
64	(0.1170)	5.9330	
68	(0.1170)	5.8160	
72	(0.1170)	5.6990	
76	(0.1170)	5.5820	
80	(0.1170)	5.4650	
84	(0.0630)	5.4020	
88	(0.0630)	5.3390	
92	(0.0630)	5.2760	
96	(0.0630)	5.2130	
100	(0.0630)	5.1500	
104	(0.0630)	5.0870	
108	(0.0630)	5.0240	
112	(0.0630)	4.9610	

EXHIBIT C-15
MAINTENANCE SCENARIO 5

INITIAL AGE = 0 NORMAL MAINTENANCE PROGRAM

AGE	CHANGE IN CONDITION	NEW CONDITION	MAINTENANCE EXPENDITURES
0	N/A	7.4620	N/A
4	(0.1560)	7.3060	1,100
8	(0.1560)	7.1500	1,100
12	(0.1560)	6.9940	1,100
16	(0.1560)	6.8380	1,100
20	(0.1560)	6.6820	1,100
24	(0.1560)	6.5260	1,100
28	(0.1560)	6.3700	1,100
32	(0.1560)	6.2140	1,100
36	(0.1560)	6,0580	1,100
40	(0.1560)	5.9020	1,100
44	(0.1560)	5.7460	1,100
48	(0.1560)	5.5900	1,100
52	(0.1560)	5.4340	1,100
56	(0.1560)	5.2780	1,100
60	(0.1560)	5.1220	1,100
64	(0.1560)	4.9660	1,100

EXHIBIT C-16
MAINTENANCE SCENARIO 6

INITIAL AGE = 0 NORMAL MAINTENANCE PROGRAM
WITH ADDITIONAL PAINTING

AGE	CHANGE IN CONDITION	NEW CONDITION	MAINTENANCE EXPENDITURES	ADDL PAINTING EXPENDITURES
0	N/A	7.4620	N/A	
4	(0.1560)	7.3060	1,100	1750
8	(0.1560)	7.1500	1,100	
12	(0.0650)	7.0850	1,100	
16	(0.1560)	6.9290	1,100	
20	(0.1560)	6.7730	1,100	
24	(0.1560)	6.6170	1,100	1975
28	(0.0650)	6.5520	1,100	
32	(0.1560)	6.3960	1,100	
36	(0.1560)	6.2400	1,100	
40	(0.1560)	6.0840	1,100	2175
44	0.4290	6.5130	1,100	
48	(0.1560)	6.3570	1,100	
52	(0.1560)	6.2010	1,100	
56	(0.1560)	6.0450	1,100	
60	(0.1560)	5.8890	1,100	
64	(0.1560)	5.7330	1,100	
68	(0.1560)	5.5770	1,100	
72	(0.1560)	5.4210	1,100	
76	(0.1560)	5.2650	1,100	
80	(0.1560)	5.1090	1,100	
84	(0.1560)	4.9530	1,100	

Exhibit C-17 shows the life-cycle costs of the maintenance scenarios for new bridges. Comparison of the first three scenarios shown in the exhibit reveals that the extended life provided by painting lowers the life-cycle cost of building and maintaining a bridge. The second scenario saves $528 annually, in constant dollars, over the no maintenance scenario. Over 50 years, this savings would be $26,400. Lesser savings are projected for less frequent painting associated with the third scenario.

Comparing the more realistic scenarios (the fourth and fifth ones in Exhibit C-17) indicates that enhancing the normal maintenance program with more frequent painting could result in annual savings of $649. Over a 50-year period, these savings would be $32,450. The sum is significant given the large number of bridges maintained by each state.

EXHIBIT C-17
LIFE CYCLE COST BY MAINTENANCE SCENARIO
FOR NEW BRIDGES

SCENARIO	EXHIBIT REFERENCE	EXPECTED LIFE (YEARS)	LIFE CYCLE COST (ANNUALIZED COST)
No Maintenance	C-11	78	$15,263
Painting in Years 14, 30, 46, and 62	C-13	130	14,735
Painting in Years 22 and 46	C-14	110	14,797
Normal Maintenance	C-15	62	15,484
Normal Maintenance With Additional Painting	C-16	82	14,835

Conclusions

The scenarios presented above are meant to reveal both the potential strengths and the apparent weaknesses of the methodology developed for examining alternative bridge maintenance programs. The deficiencies in the methodology relate to inadequacies in data available to states to examine the effects of maintenance activities on bridge condition and life expectancy. At the same time, insofar as the data base deficiencies can be resolved, the scenarios suggest that the methodology could be a very useful tool for identifying cost-effective bridge maintenance policies and programs.

REFERENCES

C-1. LINDEN, P. J., *National Bridge Inventory Report Generator Program Documentation.* Bridge Division, Federal Highway Administration, Washington, D.C. (1980).

C-2. *Policy and Procedure Manual for the Appraisal and Inventory Section.* Bridge Maintenance Unit, North Carolina Department of Transportation, Raleigh (Rev. Feb. 1984).

C-3. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges.* Federal Highway Administration, Washington, D.C. (Jan. 1979).

C-4. HYMAN, W. A. AND HUGHES, D. J. *A Computer Model for Life Cycle Cost Analysis of Statewide Bridge Repair and Replacement Needs.* Division of Planning and Budget, Wisconsin Department of Transportation, Madison (Jan. 1983).

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