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Development of a Network Optimization System

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Arizona Department of Transportation

by

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16. Abstract

A network optimization system (NOS) was developed to assist the Arizona Department of Transportation (ADOT) establish statewide pavement rehabilitation policies. This completes the final phase in development of a pavement management system for the ADOT. The NOS provides a systematic, consistent, and theoretically sound method for determining the most cost-effective rehabilitation actions for different roadways in the state to achieve and maintain desired performance standards. This report describes the development of the optimization algorithm used in the NOS, testing of the NOS with illustrative examples and an assessment of the results of the illustrative examples, and includes a discussion of whether the NOS could be implemented by the ADOT.

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ABSTRACT

A network optimization system (NOS) was developed to assist the Arizona Department of Transportation (ADOT) establish statewide pavement rehabilitation policies. This completes the final phase in development of a pavement management system for the ADOT. The NOS provides a systematic, consistent, and theoretically sound method for determining the most cost-effective rehabilitation actions for different roadways in the state to achieve and maintain desired performance standards. This report describes the development of the optimization algorithm used in the NOS, testing of the NOS with illustrative examples and an assessment of the results of the illustrative examples, and includes a discussion of whether the NOS could be implemented by the ADOT.

A set of computer programs was developed to implement the optimization algorithm used in the NOS. The output of the computer programs can be used for two functions: (1) to determine the rehabilitation policies that achieve prescribed performance standards at a minimum cost, and (2) by iteration, to determine the highest performance standards that can be maintained with a fixed budget.

The NOS can be used to prepare 1-year, 5-year, and 10-year pavement rehabilitation budgets required to maintain desired performance standards, and to allocate statewide pavement rehabilitation funds.

BACKGROUND

A pavement management system (PMS) can be defined as the systematic development of information and procedures necessary to optimize the design and rehabilitation of pavements. The PMS can be used by decision makers to determine the what, where, and when of pavement design and rehabilitation; what type of design and rehabilitation to select; and where and when rehabilitation should be performed.

The Arizona Department of Transportation (ADOT) initiated a 3-phase study to develop a PMS. This report describes the work accomplished in Phase 3 of the study that completes the development of a comprehensive PMS for the ADOT.

The three phases of this study were as follows.

Phase 1. Development of a Project Optimization System

This study, in which a procedure was developed to determine the most cost-effective pavement design and rehabilitation actions for a given roadway project over a desired analysis period (e.g., 15 to 20 years), was completed by Woodward-Clyde Consultants (WCC) for the ADOT.

Phase 2. Development of Data Base and Verification of Performance Prediction Models

In this study, the ADOT research staff designed a computerized data management system for the storage and retrieval of pavement inventory data. The performance prediction models developed in Phase 1 and Phase 3 were verified against the data collected for a representative sample of pavement projects to improve the previous models.

Phase 3. Development of a Network Optimization System

WCC conducted this study, the objective of which was to develop a systematic procedure for decisions regarding the most cost-effective pavement rehabilitation actions for the statewide highway network.

In this procedure, budgetary constraints and desired performance standards for roads in different functional classes (e.g., different volumes of traffic) were considered.

INTRODUCTION

Preserving an existing highway network in satisfactory condition requires the proper rehabilitation of deteriorating pavements. The selection of rehabilitation policies for different roads in the network is influenced by a number of factors including pavement condition, traffic volume, environmental effects, desired performance standards, and budgetary constraints. Since rehabilitation actions affect the scheduling of work and allocation of resources (dollars, personnel, and equipment), proper selection of such actions is crucial to the most efficient use of limited resources.

The Network Optimization System (NOS) developed in this study provides a systematic, consistent, and theoretically sound method for determining the most cost-effective rehabilitation actions for different roads in the network to achieve desired performance standards. The NOS is designed to accept the goals or standards set by the management for network performance as inputs. The output of the NOS provides consistent and objective information that can be used in making policy decisions of pavement rehabilitation and preparing short- and long-term rehabilitation budgets.

The next three sections of the report desribe the research approach, the description of the methodology, and the development of the optimization model. Testing and appraisal of the NOS and its implementation are discussed in the following sections. The final section contains a summary and conclusions. Technical details of the optimization algorithm and the computer program developed for this study are included in appendices.

Scope of the Study

Current budgeting procedures of the ADOT divide the total highway budget into four categories--construction, pavement preservation, maintenance, and operations. The NOS is designed to optimize the use of funds allocated to routine maintenance and preservation of pavements. In this report, the sum of funds allocated to these two activities is termed "pavement rehabilitation budget."

Construction requirements associated with increases in traffic capacity and safety are considered to be site-specific and will be identified by the priority rating system used by the ADOT. Funds for such improvements would be obtained from the construction part of the budget. In addition, those pavements deficient in skid properties will be identified by the pavement management information system (PMIS). Those sections requiring rehabilitation in the form of an overlay or seal coat will automatically be corrected for surface deficiencies. Those sections that are not corrected by appropriate rehabilitation actions will need to be improved. Funds for such improvements will be made available from special budget allocations designated for such improvements. It is anticipated that appropriate amounts of money for such purposes can be allocated based on historical experience.

RESEARCH APPROACH

The following tasks were undertaken to accomplish the project objectives.

Task 1. Establish Requirements for the NOS and Review Current Procedures

The objective of this task was to determine how the NOS was expected to be used by decision makers in the formulation of rehabilitation policies. Meetings were organized with the research staff of the ADOT to discuss expected inputs to and outputs from the system, and possible constraints (e.g., resource constraints, minimum performance standards) to be satisfied by the system. A presentation was made to the Pavement

Management Steering Committee in which the features of a conceptual NOS were presented. Middle and higher management participated in this meeting including the Director of the Department of Transportation; State Highway Engineer, Deputy and Assistant State Highway Engineers; Development, Operations, Transportation Planning, Maintenance, Information System Group, Research, and Materials department managers; and representatives of the Federal Highway Administration. Comments of the members of the Pavement Management Steering Committee were taken into account when the requirements for the NOS were finalized.

The second aspect of this task was to obtain information about current procedures used by the ADOT in the selection of rehabilitation policies and the preparation and allocation of rehabilitation budgets. Meetings were held with members of the Priority Planning Group and Administrative Services Division to discuss current procedures and how the NOS could be made compatible with such procedures.

Task 2. Develop a Conceptual Methodology for the NOS

Two alternative approaches were considered for the development of an optimization model--the maximization of benefits, and the minimization of costs.

Maximization of Benefits. In this approach, optimum rehabilitation actions are determined by maximizing highway user benefits subject to the constraints of the available budget.

Minimization of Costs. In this approach, decision makers prescribe performance standards for different roadways in the network and rehabilitation actions that achieve the desired standards with minimum cost are determined.

The second approach was used in this study because it was preferred by the management of the ADOT.

Task 3. Develop Operational Models for the Methodology

This task primarily involved the development of cost and performance prediction models. Data on a sample of the state highway network was collected and compiled by the ADOT research staff. The data included routine maintenance costs of pavements in different conditions, construction costs of various pavement rehabilitation actions, and performance histories of pavements with different characteristics (such as traffic, environmental region, deflection, age, current condition, and type of initial design and overlay).

The sample data base was used to develop prediction models for maintenance and rehabilitation costs and pavement performance under different rehabilitation actions.

Task 4. Develop Computer Programs to Implement the Optimization Model

A set of computer programs was developed to implement the optimization model selected in the previous task. The following criteria were used to design the computer programs.

- The programs should run efficiently on the computer facilities currently available to the ADOT.

- The programs should be modular, i.e., major components of the system (e.g., cost and performance models, desired performance standards) should be developed individually and included in separate modules (subroutines). With this feature, a given component of the system can be revised without having to change other components. Thus, the computer programs can be easily updated.

- The programs should be designed for use by highway engineers. This means inputs requiring some knowledge of optimization theory should be generated internally in the program. Only engineering inputs should be required of the user.

- The design of the computer programs should enable sensitivity analyses to be conducted. Thus, the user will be able to evaluate the influence of changes in major assumptions and parameters (e.g., construction costs, budget allocations, minimum performance standards) on the final results.

- The results of the program should enable users to prepare pavement rehabilitation budgets and formulate rehabilitation policies. Site-specific rehabilitation actions will be subject to more detailed engineering analysis; however, target requirements for cost and performance should be provided by the NOS results.

Task 5. Test the NOS and Revise the Model as Necessary

The NOS was tested with both hypothetical and real examples. The primary objective was to determine whether the results of the computer programs were sensible and intuitively satisfactory. It was also necessary to check whether specific changes in input data produced expected changes in the results. For example, if minimum standards are raised, the cost of rehabilitation actions to meet the standards should increase.

Data for the real examples were obtained from the ADOT research staff. The data included cost information on pavement rehabilitation and maintenance and current network condition. Desired performance standards for different functional road classes were provided by the ADOT management.

Results of the testing were discussed with the ADOT research staff and were also presented to the Pavement Management Steering Committee. Those changes that were suggested in the discussions and that seemed appropriate were made in both the model and the input data.

Task 6. Prepare a User Manual for the Computer Programs

A user manual for the computer programs was prepared that described the organization of input data, interpretation of program output, potential applications of the programs, and program capabilities and limitations. A complete documentation including listing and flow charts was also prepared.

DESCRIPTION OF THE METHODOLOGY FOR THE NETWORK OPTIMIZATION SYSTEM

A Simplified Overview of the Methodology

In order for the NOS to provide a consistent and objective basis for decision makers to choose between alternative rehabilitation policies, a methodology based on theoretically sound principles of probability theory and operations research was developed. Technical details of the methodology are described in the following parts of the report. However, to clarify the basic concepts of the methodology, a simplified overview is provided below.

A basic requirement of the NOS is that it should consider the entire road network, rather than individual projects. To accomplish this, all pavements in the network are categorized into different condition states based on factors such as roughness and cracking. The proportion of the network in each of the condition states at different time periods defines the performance of the network over time.

The ADOT management may set certain goals or standards for the network performance in terms of the minimum proportion of roads required to be in good condition states and the maximum proportion of roads allowed to be in poor condition states. The primary objective of the NOS is to determine the optimum rehabilitation action for all pavements in each condition state at different time periods. The set of rehabilitation actions should be optimum in the sense that it should achieve and maintain the prescribed performance standards with minimum cost.

The two basic requirements of this approach are:

- estimation of costs of alternative rehabilitation actions applied to pavements in a given condition state
- estimation of the proportions of all pavements in a given condition state that move to other condition states following a particular rehabilitation action.

The costs of various rehabilitation actions can be estimated based on past records and engineering judgment. Estimates of both routine maintenance costs and construction costs are required.

The proportion of roads that move from one condition state to other states following an action are obtained from the models of pavement performance. A significant factor influencing the choice of a performance prediction model for this study is that the conditions of all pavements in the network are surveyed annually. Thus, just prior to selecting a rehabilitation action for any pavement, the actual condition state will be known. The decision model, therefore, is formulated to address what rehabilitation action would be optimum for a pavement at a given time period <u>if</u> it reaches a particular condition state at the end of the previous time period. The advantage of such a formulation is that it requires the prediction of pavement performance only 1-year into the future. This eliminates the potential for large errors associated with long-term predictions. Because of this feature, the performance prediction models used in the present study have considered rate of change in the variables related to pavement performance (e.g., roughness and cracking).

Once the costs of alternative rehabilitation actions for pavements in different condition states are obtained and the proportions of pavements in a given condition state that move to other states under each action are calculated, combinations of all possible actions for all possible condition states should be studied. This is required in order to determine the set of rehabilitation actions that achieve and maintain prescribed performance standards with a minimum cost. Since an extremely large number of combinations are involved, a mathematical optimization model is generally required to implement this procedure.

The overall methodology for the NOS can be described in terms of the following components:

- selection of functional criteria and performance variables
- selection of influence variables for each performance variable
- selection of road categories and condition states
- specificaton of rehabilitation actions and policies
- development of the optimization model.

A description of each component follows.

Selection of Functional Criteria and Performance Variables

Functional criteria describe the broad areas of concern (e.g., safety, user comfort, and physical distress) that are relevant to determinations of the acceptability of pavement performance. Performance variables are physical measures of the degree to which the performance of a pavement meets various functional criteria. Examples of functional criteria are shown in Table 1.

In this study, rutting, excess user cost due to traffic delays, and vehicle operating costs were excluded as performance variables and skid number was considered separately for the reasons discussed in the following paragraphs. The methodology itself is capable of incorporating alternative performance variables that are considered relevant by the user agency.

Rutting was excluded from this study because it is not a significant problem in Arizona.

Table 1. EXAMPLES OF FUNCTIONAL CRITERIA AND PERFORMANCE VARIABLES

Functional Criteria	Performance Variables
Safety	Skid Number Rutting
Riding Comfort	Ride Index
User Convenience	Traffic Delays
User Economy	Excess User Cost
Physical Distress	Amount of Cracking

The inclusion of user costs in the NOS was considered during the planning stages of the project but has not been included in the final version. User costs, actually "excess" user costs, are associated with increased vehicle operating costs from pavement roughness or traffic delays caused by pavement roughness or construction activities. Previous experience in the development of pavement management systems has indicated that excess user cost, particularly costs related to pavement roughness, will dominate the rehabilitation and design strategies. The resulting policy requires higher performance standards that are more expensive to the financing agency when compared with analyses that do not include user costs. Also, it is not clear how the benefits of reducing user costs would accrue to highway departments in such a way as to provide increased funds necessary to maintain higher standards. Finally, present user cost data lacks sufficient documentation to justify its use as a major economic consideration.

It is pertinent to note that ADOT procedures for priority programming do inlcude an element for user costs. These considerations will continue to play a role in planning and thus, such costs are not completely neglected.

The general logic to be applied to maintaining acceptable levels of skid number is as follows.

1. All pavements with unacceptable skid number can be identified and enumerated through the pavement management information system (PMIS).

2. Those pavements scheduled for rehabilitation (e.g., seal coat, overlay, recycling) will automatically correct deficiencies in skid number.

3. Projects not scheduled for rehabilitation will be corrected under safety projects that are funded separately and are not

a part of the preservation of investment portion of the overall highway department budget.

The pavement condition surveys in the ADOT measure road roughness with Mays Ride Meter. In a previous study, roughness values (inches/mile) were found to be highly correlated with subjective panel ratings of ride index on a scale of 0 to 5. The following equation was developed to calculate ride index as a function of pavement roughness.

$$\text{Ride index} = 5.0 - (0.0155 \times \text{roughness}) + (0.001 \times (\text{roughness})^2/40.96); \quad \text{for roughness} \leq 192 \text{ inches/mile}$$

$$= \frac{100 - (0.15625 \times \text{roughness})}{24}; \quad \text{for roughness} > 192 \text{ inches/mile}$$

For this study, pavement roughness was first estimated from a performance prediction model and then converted into ride index using the above equation. Thus, the final performance variables included in the NOS were roughness and amount of cracking.

Evaluation of performance variables is generally influenced by the traffic volume on a given road. For a heavily traveled road, higher performance standards may be required. Average daily traffic (ADT) was used in this study as a variable to represent traffic volume.

Selection of Influence Variables for Each Performance Variable

Influence variables are the factors that affect the behavior of a performance variable over time. In developing a prediction equation for a performance variable, the influence variables are used as independent variables in the equation.

Table 2 shows a list of the influence variables that are relevant to the prediction of pavement roughness and amount of cracking. In order to keep the size of the NOS within manageable limits, it was necessary to limit the total number of influence variables to no more

Table 2. EXAMPLES OF INFLUENCE VARIABLES FOR PREDICTING PAVEMENT ROUGHNESS AND AMOUNT OF CRACKING

Present Roughness

Present Amount of Cracking

Deflection

Spreadability

Age

Traffic Volume (ADT)

Equivalent 18 Kip Single Axle Loads

Environment

Drainage

Structural Number

Thickness of Surface Layer

than four. The more significant influence variables for each performance variable were determined using regression analyses of sample pavement performance data collected by the ADOT. The details of regression analyses are given in Appendix B. For the reasons noted earlier, the prediction of rate of change in a performance variable was required. The influence variables included in the final regression equations are shown below.

Rate of Change in the Performance Variable	Influence Variables
Pavement roughness	Present roughness, regional factor, and rehabilitation action
Amount of cracking	Present amount of cracking, change in amount of cracking in the previous year, regional factor, and rehabilitation action

The regional factor listed above was an AASHO regional factor adjusted for the environmental conditions in Arizona. Elevation and rainfall were the primary variables used to define the regional factor on a scale of 0 to 5. The smaller numbers on the scale indicate lower elevations with relatively small amount of rainfall.

Traditional influence variables (such as deflection, spreadability, age, traffic, AC thickness) were not included because they did not show a significant (partial) correlation with the dependent variable. However, the influence of such conventional variables is indirectly included through the "pavement condition" variables. For example, a number of variables (including deflection, age, traffic, etc.) influence how the amount of cracking on a road would change over time. However, once the effect of these variables is manifested in the form of cracks in the road, the data indicate that the present amount of cracking and the rate of change in amount of cracking (i.e., how fast the amount of cracking has increased in the past year) would be the primary determinants of change in amount of cracking during the next year. Thus, the performance prediction models emphasize "what" will happen and not so much "why" changes will occur.

The main effect of different types of rehabilitation actions is on the time of crack initiation (first visible crack). For example, a thick overlay will be crack-free longer than a thin overlay. To incorporate this effect, the variable "index to first crack" was used to indicate the range of years to the first crack. Past data and engineering judgment were used to estimate the number of years to the first crack for different rehabilitation actions. The index to first crack is also a function of ADT and regional factor.

Selection of Road Categories and Condition States

The set of variables that are relevant to evaluating pavement performance includes the following:

- average daily traffic (ADT)
- regional factor
- index to first crack
- present roughness
- present amount of cracking
- change in amount of cracking during the previous year.

For purposes of the optimization algorithm (described later), the continuous variables were divided into various ranges as shown in Table 3. Each range of a variable was assumed to represent one level of the variable.

The first two variables in the above set can be considered to be independent of the rehabilitation actions applied to a pavement, i.e., the ADT and regional factors are assumed to be fixed for a given pavement. Combinations of different levels of these two variables were termed "road categories." Thus, a total of nine different road categories were defined by the discrete levels of the two variables shown in Table 3.

Table 3. RANGES SELECTED FOR DIFFERENT VARIABLES

Variable	Ranges of the Variable
ADT	1. 0 - 2,000 2. 2,001 - 10,000 3. > 10,000
Regional Factor	1. 0 - 1.7 2. 1.8 - 2.7 3. > 2.7
Index to First Crack	1. 16.1 - 20 2. 0 - 4 3. 4.1 - 8 4. 8.1 - 12 5. 12.1 - 16
Present Roughness	1. 0 - 165 2. 166 - 255 3. > 255
Present Amount of Cracking	1. 0 - 10 percent 2. 11 - 30 percent 3. > 30 percent
Change in Amount of Cracking During the Previous Year	1. 0 - 5 percent 2. 6 - 15 percent 3. > 15 percent

The remaining four variables in the above list are related to pavement condition and hence change with each rehabilitation action applied to the pavement. All four variables were relevant to predicting roughness and cracking of asphalt concrete (AC) pavements. For portland cement concrete (PCC) pavements, however, only present roughness and present amount of cracking were adequate as performance variables.

The combinations of different levels of the pavement condition variables are termed "condition states." For the discrete levels of the variables shown in Table 3, a total of 120 condition states are defined. Note that the combination of low present amount of cracking (less than 10 percent) and high change in amount of cracking during the previous year (greater than 15 percent) is not possible. Such infeasible condition states were eliminated from NOS considerations.

Specification of Rehabilitation Actions and Policies

A rehabilitation action is the type of work performed to rehabilitate a pavement to an acceptable condition, e.g., a thin overlay with asphalt concrete friction course (ACFC) or thick overlay without special treatments. One possible rehabilitation action may be to continue with only routine maintenance.

A rehabilitation policy, as determined by the NOS, assigns a rehabilitation action to pavements in each condition state and road category.

In consultation with the ADOT staff, two alternative rehabilitation actions for PCC pavements and 17 alternative rehabilitation actions for AC pavements were selected. Table 4 shows the alternative rehabilitation actions selected for PCC and AC pavements. Additional actions of recycling may have to be considered for future iterations of the NOS.

The optimization model (described in the following section) includes a provision for specification of one or more rehabilitation actions

Table 4. ALTERNATIVE REHABILITATION ACTIONS FOR AC AND PCC ROADS

AC Roads		PCC Roads	
Action Index	Action Description	Action Index	Action Description
1	Routine Maintenance Only	1	Routine Maintenance Only
2	Seal Coat	2	Grinding
3	ACFC		
4	ACFC + Asphalt rubber (AR)		
5	ACFC + Heater scarifier (HS)		
6	1.5" AC		
7	1.5" AC + AR		
8	1.5" AC + HS		
9	2.5" AC		
10	2.5" AC + AR		
11	2.5" AC + HS		
12	3.5" AC		
13	3.5" AC + AR		
14	3.5" AC + HS		
15	4.5" AC		
16	5.5" AC		
17	Recycling		

as infeasible for any given condition state. For example, if a pavement is badly cracked, rehabilitation actions that do not include a provision for correction of this condition may be specified as infeasible for roads in that condition.

DEVELOPMENT OF THE OPTIMIZATION MODEL

The primary objective of the NOS is to determine the rehabilitation policy that achieves and maintains specified performance standards for the statewide highway network with minimum cost. The performance standards may be specified in terms of minimum proportion of the network required to be in acceptable condition states and the maximum proportion of the network allowed to be in unacceptable condition states. The acceptable and unacceptable condition states are to be specified by the decision maker. For example, condition states with low roughness and low amount of cracking may be considered acceptable, while those with either high roughness or high amount of cracking may be considered unacceptable.

In order to appreciate the need for a mathematical optimization model, consider the size of the problem at hand. There are nine road categories, 120 condition states, and 17 rehabilitation actions (considering only AC pavements). For each category, 17^{120} alternative rehabilitation policies are possible! Clearly, direct examination of every possible rehabilitation policy to determine if it is feasible (i.e., satisfies the performance standards) and determination of the minimum-cost policy among all feasible policies is not practical.

The optimization model developed for this study is based on the formulation of the problem as a Markovian decision process and its conversion into a linear program. A mathematical description of the model is given in Appendix A. An informal engineering description of the model is provided in the following paragraphs.

Basic Assumptions of the Model

For purposes of the NOS it has been assumed that decisions regarding rehabilitation actions for each part of the network will be made at 1-year intervals. At the beginning of each period, the condition of each pavement is surveyed and a rehabilitation action is selected and implemented. Theoretically, these three activities are assumed to occur at a given point in time. In practice, there will be a time lag between a pavement condition survey and selection of a target action, and selection of an action and actual implementation. As long as the total time lag between a condition survey and implementation of the selected action is short (e.g., less than a unit period of time), the discrete time model as assumed is still reasonable.

It is required that the long-term rehabilitation policy be stationary. A stationary policy implies that the selection of rehabilitation actions will be a function of the pavement condition state and will not be affected by time. For example, assume that for the next year the model selects an ACFC for all pavements with high roughness and low amount of cracking. A stationary policy means that 5 years from now, the pavements that are found to be in the same condition state should receive the same treatment. Thus, stationary policy means a uniform policy over a long period of time, assuming that the effects of inflation are uniform for all rehabilitation actions.

If a stationary policy is adopted, after some length of time the network will achieve "steady state" condition. A steady state condition means that the proportion of roads in the network in each condition state should remain constant over time. For example, in steady state condition, a fixed (small) percentage of roads will be expected to have high roughness and low amount of cracking every year and all such roads could require a 2-inch overlay plus ACFC.

With the criteria of minimizing long-term expected average costs, the optimum policy can be obtained regardless of initial conditions of the network. After some length of time (that cannot be predicted beforehand), the steady state condition will be achieved. In practice, however, planning efforts require that a fixed time frame be specified so that steady state is achieved within that time. Hence, a short-term policy (that may be different from the long-term stationary policy, depending on the initial conditions) is sought in addition to the long-term policy. The time frame during which the short-term policy would be applicable is called the transition period.

The ADOT management should decide when (at which time period) the network should reach steady state condition. A provision will be made in the NOS for an examination of the effects of assuming different lengths of transient periods. Depending upon the current network condition, the short-term rehabilitation policies during the transient time period could be more expensive than the long-term (stationary) policy after reaching steady state condition. It is assumed that the ADOT has the flexibility to adjust the yearly rehabilitation budgets as described below.

Uniform expenditures may not be the most cost effective during the transient years after initiation of the NOS. During this initial period it may be necessary to increase the maintenance and preservation portion of the budget above a uniform or average annual rate of expenditure. Funds cannot be allocated in advance. Therefore, it may be necessary to adjust the construction portion of the budget to accommodate the pavement preservation requirements. However, the average allocations over the designated time period will not exceed the total allocation provided for that budget period. Increased allocations to the construction part of the budget may also be possible depending on the pavement maintenance and pavement preservation requirements. Based on discussions with ADOT personnel, these budget adjustments are considered feasible providing that appropriate 5-year requirements can be specified.

Current budgeting procedures of the ADOT divide the total highway budget into four categories--construction, pavement preservation, maintenance, and operations. The NOS is designed to optimize the use of funds allocated to routine maintenance and preservation of pavement procedures.

An Overview of the Model

The model determines the optimum long-term (stationary) rehabilitation policy and the optimum short-term rehabilitation policies (prior to reaching steady state) for pavements in each road category. The policies are optimum in the sense that they satisfy the prescribed performance standards with minimum cost.

The specific form of a rehabilitation policy is in terms of the proportion of roads of a given category in a condition state (say i) to which a specified rehabilitation action (say k) is applied at the beginning of the ℓ time period. The proportion can be interpreted as the probability that a given lane-mile of a pavement would be in state i at time ℓ and action k is taken. Let us denote this proportion by $w_{i,k}^{\ell}$. Assume that the system is required to achieve steady state at the beginning of the T^{th} time period. This means that there are (T-1) transient time periods.

Thus, the primary output of the NOS will be the specification of $w_{i,k}^{\ell}$ for all condition states (all i), all alternative rehabilitation actions (all k), and all time periods $\ell = 1, 2, \ldots, T$. Since the system will reach steady state at the beginning of T^{th} time period, $w_{i,k}^{T}$ will also be applicable for time periods T+1, T+2, ... (in theory, up to infinity).

The output of the NOS will enable the ADOT to address the following questions.

- What proportion of the pavements in each road category will be expected to be in various condition states at the beginning of each time period?

- What is the most cost-effective rehabilitation action for every mile of pavement in the network at each time period?

- What is the expected annual cost of pavement rehabilitation and routine maintenance?

It should be noted that the basic output of the optimization model does not identify the rehabilitation action that should be applied to a specific pavement in the state. However, it is possible to do this by combining the model output with the data base system which stores road inventory data. Thus, the condition states of various pavements in each road category can be identified from the data base system and the results of the optimization model can then be used to determine the most cost-effective rehabilitation action to be applied to each pavement in the network.

In the following sections, some details regarding the selection of optimum long-term and short-term rehabilitation policies are provided.

Selection of Optimum Long-Term Rehabilitation Policy

Linear programming is the mathematical technique used in the optimization model. The main components of a linear program (LP) are:

- decision variables, whose values are to be determined
- objective function, which is to be maximized or minimized
- constraints, which are to be satisfied by the decision variables.

The objective function as well as the constraints must be linear functions of the decision variables.

The components of the LP to determine the optimum long-term rehabilitation policy are discussed below.

Decision Variables. In general, the decision variables are $w_{i,k}^{\ell}$, i.e., the proportion of roads in condition state i at the beginning of the

ℓth time period to which rehabilitation action k will be applied. Since a stationary policy is in effect after reaching steady state condition (i.e., from the beginning of the T^{th} time period), the decision variables for this part of the model are $w^T_{i,k}$.

Objective Function. The objective function is to minimize the long-term expected cost of rehabilitation actions including routine maintenance. Let c(i,k) be the unit cost (in dollars per square yard) of applying action k to a pavement in condition i. (Costs are assumed to be in current dollars.) Then the objective function can be stated as follows:

$$\text{Minimize} \sum_{i,k} w^T_{i,k} c(i,k) \tag{1}$$

Note that the objective function specifies average unit cost (in dollars per square yard) of a rehabilitation policy. When the average unit cost is multiplied by the total number of units (total number of square yards) in the road category, the total annual cost of a rehabilitation policy is obtained. Since the total number of units (square yards) in the road category is fixed, minimizing average unit cost also minimizes the total cost of a rehabilitation policy. Therefore, it is not necessary to multiply Equation 1 by the total number of units.

Constraints. Two types of constraints need to be considered: (1) those to be satisfied by $w^T_{i,k}$; and (2) those arising out of specified performance standards.

First consider the constraints to be satisfied by $w^T_{i,k}$. Since they are proportions, $w^T_{i,k}$ must be non-negative. Also, the sum of $w^T_{i,k}$ over all possible condition states (i.e., all i) and all possible actions (i.e., all k) should be equal to 1, since the sum will include all the pavements in the road category for which some action is taken.

Finally, $w^{T}_{i,k}$ must satisfy the steady state condition for a stationary policy to be selected. This means that the proportion of roads that are in a given condition state (say j) at the beginning of the T^{th} period must match the expected proportions of roads that are in state j at the end of the T^{th} period (i.e., at the beginning of $(T+1)^{th}$ period). If this condition is not met, $w^{T}_{i,k}$ and w^{T+1}_{k} will not match for all values of i and k, thus violating the requirement of a stationary policy.

Another set of constraints on $w^{T}_{i,k}$ will be necessary if certain rehabilitation actions are specified as infeasible for various condition states.

The constraints on $w^{T}_{i,k}$ can be mathematically stated as follows.

$$w^{T}_{i,k} \geq 0, \text{ for all i and k} \tag{2}$$

$$\sum_{i,k} w^{T}_{i,k} = 1 \tag{3}$$

$$\sum_{k} w^{T}_{j,k} = \sum_{i,k} w^{T}_{i,k} p_{ij}(a_k), \text{ for all j} \tag{4}$$

$$w^{T}_{i,k} = 0, \text{ if } k^{th} \text{ rehabilitation action is infeasible for } i^{th} \text{ condition state} \tag{5}$$

in which $p_{ij}(a_k)$ is the proportion of roads that move from state i to state j in one time period if k^{th} action is applied to the road at the beginning of the period.

Next, consider the constraints that arise out of the specification of performance standards. The performance standards may state the minimum proportion (say ε) of the network that must be in acceptable condition states and the maximum proportion (say Υ) of the network allowed to be in unacceptable condition states. In terms of the decision variables, $w^T_{i,k}$ these requirements can be stated as follows.

$$\sum_{\substack{\text{acceptable}\\ \text{states, } k}} w^T_{i,k} \geq \varepsilon \tag{6}$$

$$\sum_{\substack{\text{unacceptable}\\ \text{states, } k}} w^T_{i,k} \geq \Upsilon \tag{7}$$

Different sets of acceptable (or unacceptable) states and minimum (or maximum) proportions may be specified.

Selection of Optimum Short-Term Rehabilitation Policies

The short-term rehabilitation policies apply to the transient time periods 1, 2, ..., T-1. A steady state condition (and a stationary policy) is not required during these time periods, although the condition to be achieved at the end of $(T-1)^{th}$ period must be the same as that specified by the long-term policy (i.e., steady state should be achieved at the end of the transition period).

Decision Variables. The decision variables are $w^{\ell}_{i,k}$ for all i and k, and $\ell = 1, 2, \ldots, T-1$. In contrast, the decision variables for the long-term policy section were $w^T_{i,k}$.

Objective Function. The total cost of rehabilitation actions during the time periods $\ell = 1, 2, \ldots, T-1$ is to be minimized. Thus, the objective function is:

Minimize $$\sum_{i,k,\ell} w_{i,k}^{\ell} d_{\ell} c(i,k), \qquad \ell = 1, 2, \ldots, T-1 \tag{8}$$

in which d_{ℓ} is the discount factor, i.e., the present work of one dollar spent during the ℓ^{th} time period.

Constraints. The decision variables $w_{i,k}^{\ell}$ must be non-negative. At the beginning of the first period, the proportions of the roads in various condition states will be known. Let q_i denote the (known) initial proportion of roads in state i. The proportion of roads in state i for which some action is applied at the beginning of the first time period must match q_i. In addition, the proportion of roads that are in a state (say i) at the beginning of the ℓ^{th} period must match with the proportion of roads that would be in state i at the end of $(\ell-1)^{th}$ period. These constraints can be stated as follows.

$$w_{i,k}^{\ell} \geq 0, \text{ for all i and k, and } \ell = 1,2,\ldots,T-1 \tag{9}$$

$$\sum_{i,k} w_{i,k}^{\ell} = q_i, \text{ for all i} \tag{10}$$

$$\sum_{k} w_{j,k}^{\ell} = \sum_{i,k} w_{i,k}^{\ell-1} p_{ij}(a_k), \text{ for all j, and } \ell = 1,2,\ldots,T-1 \tag{11}$$

The network is required to attain the steady condition at the beginning of T^{th} period. Since the optimum steady state (stationary) policy is already determined from Equations 1 through 7, the proportions of pavements in various states at the beginning of the T^{th} period must match (within small tolerances) with the corresponding proportions of the optimum stationary policy. In addition, the cost at the T^{th} period should match with that of the optimum stationary policy. Therefore, the following constraints are placed on the solution.

$$\sum_{k} w^{T}_{j,k} \geq \sum_{k} w^{*}_{j,k}(1-\alpha) \tag{12}$$

$$\sum_{k} w^{T}_{j,k} \leq \sum_{k} w^{*}_{j,k}(1+\alpha) \tag{13}$$

$$\sum_{i,k} w^{T}_{i,k} c(i,k) \leq c^{*}(1+\beta) \tag{14}$$

in which $w^{*}_{j,k}$ are proportions in the optimum stationary policy determined previously, c^{*} is the cost of that policy, and α and β are specified tolerances (e.g., 0.01).

The constraints 12 and 13 move the system to converge (within small tolerances) on the optimum stationary policy obtained previously.

Constraint 14 requires that the cost at the T^{th} time period should be within a small percentage of the cost of the optimum stationary policy.

If certain rehabilitation actions are infeasible for some condition states, the set of constraints shown in Equation 5 will be required.

In order that the roads provide reasonable performance during the transient time periods, performance standards for such periods will be required. Without such standards, the model may select a policy that permits roads to remain in poor condition for first (T-2) periods and requires very expensive actions for the $(T-1)^{th}$ period in order to achieve the optimum stationary policy at the T^{th} period. This, although optimum from the standpoint of minimizing total expected discounted costs over the transition period, may not be acceptable because of a relatively high number of poor condition roads during the initial period.

The same performance standards for transient periods as those for the steady state conditions may be required. However, this requirement may result in expensive rehabilitation policies if the existing network condition is too far below the required standards. For this reason, a provision is made to specify less stringent standards for the transient periods if so desired by the management. This is done by specifying two multipliers, $p_1(\ell)$ and $p_2(\ell)$, for each time period except for the first and the T^{th} time periods. The effect of the multipliers on the constraints of performance standards is shown below.

$$\sum_{\substack{\text{acceptable} \\ \text{states, } k}} w^{\ell}_{i,k} \geq p_2(\ell)\varepsilon, \quad \text{for } \ell = 2,3,\ldots,T-1 \qquad (15)$$

$$\sum_{\substack{\text{unacceptable}\\ \text{states, } k}} w^{\ell}_{i,k} \leq p_1(\ell)\gamma, \text{ for } \ell = 2,3,\ldots,T-1 \tag{16}$$

As seen in the above equations, the multipliers $p_1(\ell)$ and $p_2(\ell)$ indicate the amounts by which the steady state performance standards, ε and γ can be relaxed. The multiplier $p_2(\ell)$ should always be less than or equal to 1 and $p_1(\ell)$ greater than or equal to 1. for example, let the steady state performance standards be $\varepsilon = 0.7$ and $\gamma = 0.1$. This means that, after reaching steady state, the condition of at least 70 percent of all roads should be acceptable and the condition of no more than 10 percent should be unacceptable. No specific performance standards are required for the remaining 20 percent. Now assume $p_2(2) = 0.8$ and $p_1(2) = 1.2$. This means that, at the beginning of the second period, the management is willing to accept a minimum of (0.7 x 0.8) or 56 percent of roads in acceptable condition, and a maximum of (1.2 x 0.1) or 12 percent of roads in unacceptable condition.

Since the current network proportions in different states are known (and fixed) and the proportions at the beginning of T^{th} period should match the steady state requirements, the multipliers should not be specified for the 1^{st} and T^{th} period.

TESTING AND APPRAISAL OF THE NETWORK OPTIMIZATION SYSTEM

The NOS was tested by examining whether (1) the short-term and long-term optimum rehabilitation policies selected by the system for current roadway conditions in Arizona were sensible and intuitively satisfactory, and (2) specified changes in important input parameters produced expected modifications in the optimum rehabilitation policies.

Time and budgetary constraints necessitated that testing be done primarily on AC pavements. The proportion of PCC pavements in Arizona is small. In addition, the size of the problem (number of condition states and rehabilitation actions) for PCC pavements is considerably smaller than for AC pavements. The analysis of the more complex problem (of AC pavements) was considered adequate in testing the main features of the system. The NOS itself, of course, is designed to include both AC and PCC pavements.

The main components in testing the NOS were:

- defining model parameters
- assessing input data
- implementing computer programs to determine optimum rehabilitation policies
- describing results of illustrative examples
- assessing results of illustrative examples
- appraising the NOS.

Defining Model Parameters

The important model parameters are road categories, alternative rehabilitation actions, and condition states. Nine road categories were defined corresponding to the combinations of discrete levels of ADT and regional factor shown in Table 3. The alternative rehabilitation actions shown in Table 4 were considered for the test examples. Combinations of different levels of four condition variables (index to first crack, present roughness, present amount of cracking, and change in amount of cracking during the previous year) resulted in 120 condition states.

Assessing Input Data

The inputs required for the NOS include the costs of rehabilitation actions, transition probabilities, infeasible rehabilitation actions, and performance standards.

Costs of Rehabilitation Actions.

The optimization model requires estimates of c(i,k)--the cost of k^{th} rehabilitation action for a pavement in i^{th} condition state. The total cost of a rehabilitation action consists of the following two components.

- Construction cost. This is the contract cost of completing a rehabilitation action according to the specifications. For text examples, it was assumed that the construction cost is a function of the action only, and did not depend on the pavement condition.

- Routine maintenance cost. This is the cost of the annual pavement maintenance performed routinely by the department. The routine maintenance cost is a function of the pavement condition following the rehabilitation action.

The total cost, c(i,k) can be calculated from

$$c(i,k) = cr(k) + rm(i,k) \tag{17}$$

in which cr(k) = construction costs of the k^{th} action, and rm(i,k) = routine maintenance cost on a pavement in i^{th} condition state following k^{th} action.

Estimates of construction costs were made by the ADOT based on their current records of contract costs for various rehabilitation actions. The basic cost data is listed in Table 5. The construction costs of various rehabilitation actions were calculated with this data, the results of which are shown in Table 6.

With respect to routine maintenance costs, a sample of pavements in different conditions was selected and the cost of routine maintenance performed on these pavements was found from the maintenance management system (PECOS) used by the ADOT. A regression analysis was conducted to estimate routine maintenance costs as a function of pavement condition. The roughness (equivalent to the ride index) of a pavement and amount of cracking were found to be the main variables that significantly influenced routine maintenance costs. The following regression equation was obtained:

Table 5. BASIC COST DATA FOR VARIOUS REHABILITATION ACTIONS

Action	Unit Cost in $/square yard
Seal Coat	0.55
ACFC	0.75
1 inch of AC	1.05
Asaphalt Rubber	1.30
Heater Scarifier	1.00
Concrete Grinding	6.00

Table 6. CONSTRUCTION COSTS OF VARIOUS REHABILITATION ACTIONS

Action Index	Action Description	Unit Construction Cost $/square yard
1	Routine Maintenance	0
2	Seal Coat	0.55
3	ACFC	0.75
4	ACFC + (AR)	2.05
5	ACFC + (HS)	1.75
6	1.5 inch AC	1.575
7	1.5 inch AC + AR	2.875
8	1.5 inch AC + HS	2.575
9	2.5 inch AC	2.625
10	2.5 inch AC + AR	3.925
11	2.5 inch AC + HS	3.625
12	3.5 inch AC	3.675
13	3.5 inch AC + AR	4.975
14	3.5 inch AC + HS	4.675
15	4.5 inch AC	4.725
16	5.5 inch AC	5.775
17	Recycling (equivalent to 6 inches AC)	6.30

Routine maintenance cost in dollars per lane-mile
= 950 - (200 x ride index) + (43 x percent cracking).

As the ride index of a pavement decreases (i.e., the pavement becomes rougher) and the percent cracking increases, the routine maintenance costs increase.

To calculate the routine maintenance cost of a pavement after a particular rehabilitation action is taken, the condition of the pavement immediately after the action must be found. Based on the past performance of pavements in Arizona, it is reasonable to assume that the amount of cracking on a pavement is brought to zero following any rehabilitation action except for routine maintenance only. In addition, the roughness of a pavement immediately following a rehabilitation action (except for the routine maintenance and seal coat actions) is observed to be in the range 120 ± 45 (corresponding to a ride index of 3.5 ± 0.5). In general, routine maintenance alone does not significantly improve pavement roughness or cracking.

The above information provides estimates of roughness (and hence ride index) and cracking of a pavement immediately after implementing various rehabilitation actions. Using these estimates in Equation 18, routine maintenance costs of rehabilitation actions for different pavement conditions were calculated. The costs (after converting to dollars per square yard) are shown in Table 7. An average lane-width of 12 feet was assumed in converting dollars per lane-mile to dollars per square yard.

<u>Transition Probabilities</u>. The transition probability $p_{ij}(a_k)$ is the probability that a road state i moves to state j in one year if k^{th} rehabilitation action is applied to the road.

Ideally, the transition probabilities are obtained by observing the performance of a large number of pavements under different rehabilitation actions over a long period of time and then computing the proportion

Table 7. ROUTINE MAINTENANCE COSTS FOR VARIOUS REHABILITATION ACTIONS

1. Rehabilitation Action: Routine maintenance only

Present Roughness	Present Amount of Cracking	Routine Maintenance Cost $/square yard
120 (± 45)	5 (± 5)	0.066
"	20 (± 10)	0.158
"	45 (± 15)	0.310
210 (± 45)	5 (± 5)	0.087
"	20 (± 10)	0.179
"	45 (± 15)	0.332
300 (± 45)	5 (± 5)	0.102
"	20 (± 10)	0.193
"	45 (± 15)	0.346

2. Rehabilitation Action: Seal Coat

Present Roughness	Routine Maintenance Cost $/square yard
120 (± 45)	0.036
210 (± 45)	0.057
300 (± 45)	0.071

3. Rehabilitation Action: All Except the Above Two

Routine maintenance cost = $0.036/square yard of roads that move from state i to j in one year, following k^{th} rehabilitation action for all values of i, j, and k.

However, such large amounts of pavement performance data are currently not available in Arizona. For this reason, another approach was taken for the computation of transition probabilities. In this approach, regression equations were developed for predicting pavement performance based on a sample of available data. The generation of transition probabilities is described in Appendix B.

Infeasible Rehabilitation Actions. Two specifications of infeasible actions were made: (1) for roads with low roughness (less than or equal to 165 inches/mile) and low amount of cracking (less than or equal to 10 percent), rehabilitation actions other than routine maintenance and seal coat were considered unnecessary; and (2) for roads with high roughness (greater than 255 inches/mile) and high amount of cracking (greater than 30 percent), routine maintenance or seal coat were considered inadequate in correcting the problems of roughness and cracking.

Performance Standards. The following performance standards were specified.

1. The minimum proportion of roads required to be in a state of low roughness (less than or equal to 165 inches/mile) and low amount of cracking (less than or equal to 10 percent).

2. The maximum proportion of roads permitted to be in a state of high roughness (greater than 255 inches/mile) and high amount of cracking (greater than or equal to 30 percent).

Table 8 shows the performance standards for various traffic levels considered for the testing of the methodology. Within a given traffic level, the same performance standards applied to all environmental regions.

Table 8. PERFORMANCE STANDARDS FOR VARIOUS TRAFFIC LEVELS

Acceptable Pavement Condition:
Roughness $\leq$ 165 and Amount of Cracking $\leq$ 10%

Unacceptable Pavement Condition:
Roughness > 255 and Amount of Cracking > 30%

ADT	Minimum Proportion of Roads in Acceptable Condition	Maximum Proportion of Roads in Unacceptable Condition
< 2,000	0.25	0.25
2,001 - 10,000	0.60	0.15
> 10,000	0.75	0.10

The network was required to achieve steady state in 5 years. Thus, the performance standards in Table 8 apply to the fifth year. For years 2 through 4, the performance standards were relaxed by specifying the multipliers $p_1(\ell)$ and $p_2(\ell)$ for $\ell = 2, 3, 4$ (see Equations 15 and 16). These multipliers are shown in Table 9.

Implementation of Computer Programs to Determine Optimum Rehabilitation Policies

A set of computer programs was developed to implement the optimization algorithm described in the previous section. A user manual that describes input-output characteristics of the programs and a stepwise procedure for using the programs to determine optimum short-term and long-term rehabilitation policies is contained in Appendix A. The stepwise procedure in the user manual was used to obtain optimum policies for AC pavements in different road categories. The results of the computer programs are presented and discussed in the following section.

Description of Results of Illustrative Examples

Two sets of results were obtained: (1) optimum long-term rehabilitation policies, and (2) optimum short-term rehabilitation policies. Each set of results is described below. An assessment of the results is contained in a following section.

Optimum Long-Term Rehabilitation Policies.

The long-term policy is applicable afer the network reaches steady state. As stated earlier, the network was required to be in steady state at the beginning of the fifth year.

The long-term optimum rehabilitation policies for all road categories (i.e., all combinations of traffic and region) were determined. As an illustration of these results, the optimum long-term policy for roads with ADT > 10,000 and regional factor $\leq$ 1.7 is shown in Figure 1.

The following trends are observed in the results.

Table 9. MULTIPLIERS $p_1(\ell)$ AND $p_2(\ell)$ FOR THE ILLUSTRATIVE EXAMPLES

Year ℓ	$p_2(\ell)$	$p_1(\ell)$
2	0.4	2.0
3	0.6	1.6
4	0.8	1.3

Figure 1. AN EXAMPLE OF A LONG-TERM OPTIMUM REHABILITATION POLICY

(pages 42-44)

SELECTION OF OPTIMUM REHABILITATION POLICIES

1. Control Data

Type of Road:	AC
Traffic, ADT:	> 10,000
Regional Factor:	1.2 (±0.5)
Total Number of Square Yards:	11.48×10^6
Number of Condition States:	120

2. Desired Performance Standards

Acceptable Road Condition: Ride index ≥ 3.0 and cracking ≤ 10%

Year	Minimum Proportion Specified	Actual Proportion Achieved
Steady State	0.75	0.75

Unacceptable Road Condition: Ride index < 2.5 and cracking > 30%

Year	Maximum Proportion Specified	Actual Proportion Achieved
Steady State	0.10	0

3. Required Funding Levels

Year	Total Cost of Optimum Rehabilitation Policy in Millions of Dollars
Steady State	1.95

OPTIMUM REHABILITATION POLICY

Period = Steady State

State Index	Index to First Crack	Present Roughness	Present Cracking in Percent	Change in Cracking in 1 Year	Recommended Action	Proportion of Roads	Annual Unit Cost $/square yard
25	2(±2)	120(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.750	0.066
28	2(±2)	120(±45)	20(±10)	10(±5)	Seal Coat	0.100	0.586
33	2(±2)	210(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.039	0.087
	2(±2)	210(±45)	5(±5)	2.5(±2.5)	ACFC	0.048	0.786
36	2(±2)	210(±45)	20(±5)	10(±5)	ACFC	0.013	0.786
41	2(±2)	300(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.042	0.102
44	2(±2)	300(±45)	20(±10)	10(±5)	ACFC	0.007	0.786

Total Average Cost, $/square yard = 0.17

1. If a pavement has low roughness (less than or equal to 165 inches/mile) and low cracking (less than or equal to 10 percent), the "Routine Maintenance" action is selected.

2. If a pavement has low roughness, but medium (10.1 to 30 percent) or high (greater than 30 percent) cracking, the program generally selects "seal coat," but in some instances "ACFC" is also selected. (Note that a seal coat may be considered infeasible for ADT greater than 10,000 and may be so specified for the NOS as a policy decision.)

3. If a pavement has medium (166 to 255 inches/mile) or high (greater than 255 inches/mile) roughnes and/or medium or high cracking, the "ACFC" action is selected.

4. Overlays, other than ACFC, were not selected in this example; further discussion of this trend is included under "Assessment of Results."

Optimum Short-Term Rehabilitation Policies. The network was assumed to begin with the current condition of roads in a given category. The policies that minimized the total cost within the first 4 years and brought the network to steady state at the beginning of the fifth year were determined. As an illustration of the results, the optimum short-term policies for roads with ADT > 10,000 and regional factor $\leq$ 1.7 are shown in Figure 2. Figure 3 summarizes the expected performance and cost of the optimum policies.

The important trends of the optimum short-term policies include the following.

1. If the roads in a given category are in good condition at the present time, the cost of the optimum policy is low for the first 1 or 2 years. Then the cost increases and finally adjusts to the steady state cost.

Figure 2. EXAMPLES OF SHORT-TERM OPTIMUM REHABILITATION POLICIES

(pages 46-53)

SELECTION OF OPTIMUM REHABILITATION POLICIES

1. Control Data

Type of Road:	AC
Traffic, ADT:	> 10,000
Regional Environmental Factor:	1.2 (±0.5)
Total Number of Square Yards:	11.48×10^6
Number of Condition States:	120

2. Desired Performance Standards

Acceptable Road Condition: Ride index ⩾ 3.0 and cracking ⩽ 10%

Year	Minimum Proportion Specified	Actual Proportion Achieved
1	--	0.77
2	0.30	0.70
3	0.45	0.60
4	0.60	0.85
5	0.75	0.75

Unacceptable Road Condition: Ride index < 2.5 and cracking > 30%

Year	Maximum Proportion Specified	Actual Proportion Achieved
1	--	0
2	0.20	0
3	0.16	0
4	0.13	0
5	0.10	0

3. Required Funding Levels

Year	Total Cost of Optimum Rehabilitation Policy in Millions of Dollars
1	1.34
2	1.03
3	5.85
4	1.93
5	1.95

OPTIMUM REHABILITATION POLICY

Period = 1

State Index	Index to First Crack	Present Roughness	Present Cracking in Percent	Change in Cracking in 1 Year	Recommended Action	Proportion of Roads	Annual Unit Cost $/square yard
1	18(±2)	120(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.768	0.066
2	18(±2)	120(±45)	5(±5)	10(±5)	Routine Maintenance	0.009	0.066
3	18(±2)	120(±45)	20(±10)	2.5(±2.5)	Routine Maintenance	0.069	0.158
4	18(±2)	120(±45)	20(±10)	10(±5)	Routine Maintenance	0.006	0.158
6	18(±2)	120(±45)	45(±15)	2.5(±2.5)	Seal Coat	0.010	0.586
7	18(±2)	120(±45)	45(±15)	10(±5)	Seal Coat	0.001	0.586
9	18(±2)	210(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.076	0.087
11	18(±2)	210(±45)	20(±10)	2.5(±2.5)	ACFC	0.014	0.786
14	18(±2)	210(±45)	45(±15)	2.5(±2.5)	ACFC	0.002	0.786
15	18(±2)	210(±45)	45(±15)	10(±5)	ACFC	0.005	0.786
17	18(±2)	300(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.014	0.102
19	18(±2)	300(±45)	20(±10)	2.5(±2.5)	ACFC	0.027	0.786
22	18(±2)	300(±45)	45(±15)	2.5(±2.5)	ACFC	0	0.786

Total Annual Cost, $/square yard = 0.117

OPTIMUM REHABILITATION POLICY

Period = 2

State Index	Index to First Crack	Present Roughness	Present Cracking in Percent	Change in Cracking in 1 Year	Recommended Action	Proportion of Roads	Annual Unit Cost $/square yard
1	18(±2)	120(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.649	0.066
3	18(±2)	120(±45)	20(±10)	2.5(±2.5)	Routine Maintenance	0.066	0.158
4	18(±2)	120(±45)	20(±10)	10(±5)	Routine Maintenance	0.066	0.158
7	18(±2)	120(±45)	45(±15)	10(±5)	Seal Coat	0.002	0.586
9	18(±2)	210(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.113	0.087
11	18(±2)	210(±45)	20(±10)	2.5(±2.5)	ACFC	0.006	0.786
12	18(±2)	210(±45)	20(±10)	10(±5)	Routine Maintenance	0.011	0.179
15	18(±2)	210(±45)	45(±15)	10(±5)	ACFC	0	0.786
17	18(±2)	210(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.025	0.102
20	18(±2)	210(±45)	20(±10)	10(±5)	ACFC	0.002	0.786
25	2(±2)	120(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.054	0.066
33	2(±2)	210(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.005	0.087
41	2(±2)	300(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.001	0.102

Total Annual Cost, $/square yard = 0.090

OPTIMUM REHABILITATION POLICY

Period = 3

State Index	Index to First Crack	Present Roughness	Present Cracking in Percent	Change in Cracking in 1 Year	Recommended Action	Proportion of Roads	Annual Unit Cost $/square yard
1	18(±2)	120(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.117	0.066
	18(±2)	120(±45)	5(±5)	2.5(±2.5)	Seal Coat	0.430	0.586
3	18(±2)	120(±45)	20(±10)	2.5(±2.5)	Seal Coat	0.098	0.586
4	18(±2)	120(±45)	20(±10)	10(±5)	Seal Coat	0.050	0.586
7	18(±2)	120(±45)	45(±15)	10(±5)	Seal Coat	0.024	0.586
9	18(±2)	210(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.027	0.087
	18(±2)	210(±45)	5(±5)	2.5(±2.5)	ACFC	0.105	0.786
11	18(±2)	210(±45)	20(±10)	2.5(±2.5)	ACFC	0.014	0.786
12	18(±2)	210(±45)	20(±10)	10(±5)	ACFC	0.012	0.786
15	18(±2)	210(±45)	45(±15)	10(±5)	ACFC	0.006	0.786
17	18(±2)	300(±45)	5(±5)	2.5(±2.5)	Seal Coat	0.035	0.621
	18(±2)	300(±45)	5(±5)	2.5(±2.5)	ACFC	0.006	0.786
19	18(±2)	300(±45)	20(±10)	2.5(±2.5)	ACFC	0.001	0.786
20	18(±2)	300(±45)	10(±10)	2.5(±2.5)	ACFC	0.004	0.621
23	18(±2)	300(±45)	20(±10)	10(±5)	Seal Coat	0.001	0.786
25	2(±2)	120(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.052	0.066
28	2(±2)	120(±45)	20(±10)	10(±5)	Seal Coat	0.007	0.586

OPTIMUM REHABILITATION POLICY

Period = 3 (continued)

State Index	Index to First Crack	Present Roughness	Present Cracking in Percent	Change in Cracking in 1 Year	Recommended Action	Proportion of Roads	Annual Unit Cost $/square yard
33	2(±2)	210(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.008	0.087
36	2(±2)	210(±45)	20(±10)	10(±5)	ACFC	0.001	0.786
41	2(±2)	300(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.002	0.102
44	2(±2)	300(±45)	20(±10)	10(±5)	Seal Coat	0	0.621

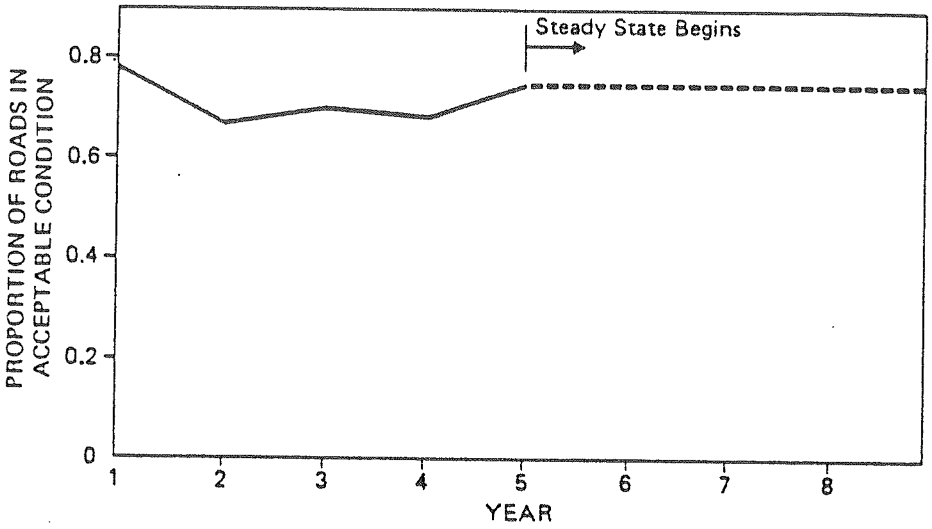
Total Average Cost, $/square yard = 0.510

OPTIMUM REHABILITATION POLICY

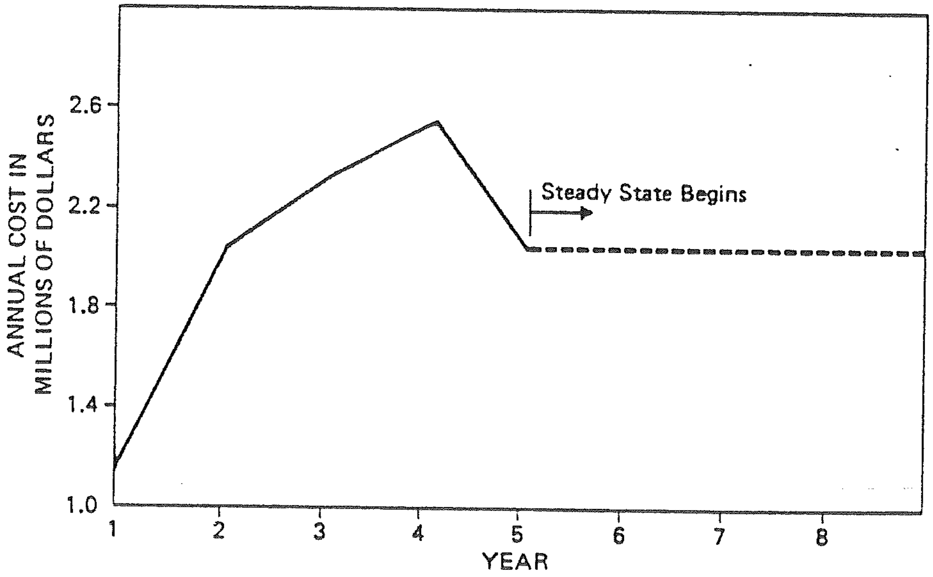
Period = 4

State Index	Index to First Crack	Present Roughness	Present Cracking in Percent	Change in Cracking in 1 Year	Recommended Action	Proportion of Roads	Annual Unit Cost $/square yard
1	18(±2)	120(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.004	0.066
	18(±2)	120(±45)	5(±5)	2.5(±2.5)	Seal Coat	0.095	0.586
4	18(±2)	120(±45)	20(±10)	10(±5)	Seal Coat	0.009	0.586
9	18(±2)	210(±45)	5(±5)	2.5(±2.5)	ACFC	0.029	0.786
12	18(±2)	210(±45)	20(±10)	10(±5)	ACFC	0.003	0.786
17	18(±2)	300(±45)	5(±5)	2.5(±2.5)	ACFC	0.004	0.786
20	18(±2)	300(±45)	20(±10)	10(±5)	Seal Coat	0	0.621
	18(±2)	300(±45)	20(±10)	10(±5)	ACFC	0	0.786
25	2(±2)	120(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.746	0.066
28	2(±2)	120(±45)	20(±10)	10(±5)	Seal Coat	0.007	0.586
33	2(±2)	210(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.039	0.087
	2(±2)	210(±45)	5(±5)	2.5(±2.5)	ACFC	0.020	0.786
36	2(±2)	210(±45)	20(±10)	10(±5)	ACFC	0.002	0.786
41	2(±2)	300(±45)	5(±5)	2.5(±2.5)	Routine Maintenance	0.042	0.102
44	2(±2)	300(±45)	20(±10)	10(±5)	ACFC	0	0.786

Total Annual Cost, $/square yard = 0.168



(a) Projected Performance of the Network



(b) Projected Preservation of Investment Budgets

Figure 3. EXPECTED PERFORMANCE AND COST
UNDER OPTIMUM POLICIES

2. If the current condition of roads is poor, the initial costs are high and they slowly adjust to the steady state cost.

3. Because of the relaxed performance standards for the first 4 years, the system selects "routine maintenance" for as many roads as it can without violating the required standards. If the steady state standards are not relaxed for the first 4 years, the system is likely to select more expensive rehabilitation actions for these years.

Assessment of Results of Illustrative Examples

The set of results obtained was only a first iteration in the process of selecting rehabilitation policies. Several iterations may be required before the final selection of policies is made. The following comments provide an assessment of the results obtained for the illustrative examples and suggest modifications and refinements that should be made in subsequent iterations.

- The selection of "routine maintenance" and "seal coat" appears to be reasonable. The program selects "routine maintenance when both the roughness and cracking on a road are low.

- If a road has moderate or high cracking, but low roughness, the program generally selects "seal coat." Since a seal coat corrects the cracking problem for a limited period of time (about 4 years), but has no effect on roughness, the choice of a seal coat may be appropriate, at least for low traffic roads. The program does have a provision for eliminating seal coat (and/or other actions) from policies selected for a given category of traffic and region. For categories of high traffic and urban regions, it may be appropriate to eliminate seal coat and/or ACFC from policy selection.

- The program appears to be selecting "ACFC" too often. This occurs primarily because of two conditions.

- The benefit of ACFC in reducing the roughness of a road seems to be unrealistically high. For example, if the roughness was as high as 300 prior to an ACFC, the expected roughness after the ACFC was calculated to be about 77. A more reasonable value for the expected roughness after the ACFC would be about 150. Obviously an adjustment in the prediction of roughness following an ACFC needs to be made.

- The assumed performance standards with regard to an unacceptable condition required that no more than 10 percent of roads have a roughness greater than 255 (i.e., ride index less than 2.5) and cracking less than 30 percent. A very small proportion of roads (less than 1 percent) is in the unacceptable condition at the present time. Thus, the defined unacceptable condition appears to be unreasonable in that it imposes no real constraints on the network performance. A more reasonable performance standard would be to require no more than a certain percent (e.g., 10 percent) of roads with roughness greater than 255 or cracking greater than 30 percent. This would be a more strict constraint on the system. To satisfy this constraint, the program probably would select actions other than ACFC (e.g., overlays of different thickness) for roads that have either high roughness or high cracking. Presently the program finds the ACFC to be adequate in limiting the proportion of roads in unacceptable condition within the allowable range.

- The short-term optimum rehabilitation policies generally result in a non-uniform distribution of cost in different years. Specifically, the cost during the third year appears much higher than during other years. This may be the result of requiring the network to achieve steady state in 5 years and accepting too relaxed performance standards for the first

2 years. Since the current condition of the network is generally very good, the first year cost of the optimum policy is small. Since the network is required to meet relatively modest performance standards for the second year, the program again is able to select a policy with a small cost. Now, for the third year, the performance standards become more strict and also the network has to start moving gradually towards steady state condition. Therefore, the program has to select a policy with relatively high cost to satisfy these constraints. For the fourth year, the cost of the selected policy decreases before finally leveling at the cost of the steady state solution at the beginning of the fifth year.

If a more uniform distribution of cost during the transient years is desired, greater compliance with the performance standards should be specified for the transient years. This can be done by adjusting the multipliers $p_1(\ell)$ and $p_2(\ell)$. It should be noted, however, that the total cost during the first 4 years may be higher (although more uniformly distributed) if greater compliance is specified.

- The selection of optimum rehabilitation policies is significantly influenced by the current condition of the network and the specified performance standards. The current network condition is, of course, fixed. The decision maker, however, does have control over the selection of performance standards. It is suggested that the program be run with different sets of performance standards in order to obtain a feel for how the system behaves under different standards. This information would be particularly useful when the costs of the optimum policies exceed the available budget and hence it becomes necessary to change standards in order to meet the budget constraint.

Appraisal of the NOS

The results of the illustrative examples indicate that the NOS is working properly and providing reasonable solutions. We believe, therefore, that the NOS is ready for trial implementation by the ADOT. A number of issues relevant to implementation of the NOS are discussed in the next section. In the remainder of this section, some of the significant features of the NOS are summarized.

- The NOS is a comprehensive system that addresses various aspects of pavement management including budgeting, planning, programming, monitoring, and selection of rehabilitation actions. With site-specific investigations, the NOS is also capable of considering design, construction, and maintenance of pavements.

- The methodology of the NOS uses state-of-the-art technologies to solve a very complex problem in a practical and implementable way. Although the techniques of Markovian prediction models, linear programming, and network flow theory have been used in other disciplines such as business management and space research programs, the combination of all these techniques for a single application is unique.

- The pavement performance and cost prediction models used in the NOS were developed from a large amount of real data that was collected by the ADOT staff over several years. The prediction models used in the NOS have been verified against an independent set of measured data and found to be in reasonable agreement with the data.

- The uncertainties in pavement performance are treated in the most satisfactory manner. The NOS does not require the prediction of the condition of an individual project over a long period of time (such as 15 to 20 years). Experience shows the reliability of such predictions is generally very low. What the NOS does require is the prediction of the proportion of roads in a given condition that would move to different conditions in a unit of time (e.g., 1-year) under different rehabilitation actions. It is not necessary to identify which specific roads will move to a given condition in 1-year under an action. The prediction of the proportion of roads in a given condition that move to different conditions in 1-year is much more reliable and can be done more readily. When the results of the NOS are finally used in selecting a rehabilitation action for a specific road, the selection is based on the observed condition of the road rather than its expected condition. The conditions of all roads are surveyed annually in Arizona. A system which does not (or cannot) use the latest information in the selection of rehabilitation policies would not be a very reliable system. The NOS makes the most effective use of the latest information on pavement condition before selecting an action for the pavement.

- A unique feature of the NOS is its determination of a stationary rehabilitation policy. A stationary policy means that if a pavement is observed in a given condition at any period of time, the same rehabilitation action will be optimum. A stationary policy is, therefore, a uniform and consistent policy over time. Also, if a stationary policy is followed at each period, the expected proportions of roads in different conditions (e.g., good, fair, or poor) will remain constant over time.

The NOS has a provision to bring the network from its current condition to steady state in a reasonable time period (e.g., 5 years) with minimum cost. After the steady state is reached, the stationary policy will be in effect. However, if factors such as severe winter, significant budget cuts, or changes in construction procedures change the steady state network, the NOS will again start from the changed (transient) state of the network and bring it back to steady state. Thus, the NOS is responsive to the external factors that significantly affect the network condition.

IMPLEMENTATION OF THE NETWORK OPTIMIZATION SYSTEM

The optimization algorithm and the set of computer programs developed for using the algorithm were tested to study the behavior of the NOS under different input data. The results of the test examples (described in the previous section) show that the NOS produces reasonable policies of pavement rehabilitation for assumed conditions of the pavement network in the state. Based on these results, our recommendation is that the NOS be implemented on a trial basis. The first application of the NOS would be for preparation of pavement rehabilitation budgets. It is expected that selection of rehabilitation policies would require a greater amount of testing. As necessary adjustments in the cost and performance prediction models for actual field conditions are made, and the confidence of the field and the design personnel in the system grows, a full-scale implementation of the NOS can be attempted.

In this section, we discuss the following issues relevant to a trial implementation of the NOS.

1. How would the NOS be made compatible with the existing procedures and programs used by the ADOT in selecting pavements for rehabilitation and in designing rehabilitation actions (i.e., overlays)?

2. How can the NOS be monitored to check whether it is performing in a reasonable and predicted manner?

3. What would be the staffing requirements for implementing the NOS on a statewide basis?

4. Once the NOS is implemented, how can it be used in setting rehabilitation policies and in preparing 5-year and 10-year rehabiliation budgets?

Compatibility of the NOS with Existing Procedures

Review of Existing Procedures. At the present time, the ADOT uses a Priority Rating System to determine the need for construction, reconstruction, or rehabilitation. In this system, a priority score on the scale of 0 to 200 is assigned to each road; a higher score indicates a more critical need for constructing or rehabilitating the road. The main factors used in determining the priority score of a road are the physical sufficiency of the road (i.e., its condition, serviceability, and safety design), environmental impact, socio-economic influence, and effect on traffic safety.

Environmental and economic factors are used primarily to determine the need for new construction. To determine the rehabilitation needs of existing roads, only the physical sufficiency factors are used.

Once the priorities for rehabilitation of various roads are determined, specific projects are selected from the list such that the costs of rehabilitation match the available funds. The final selection of rehabilitation projects is made in consultation between headquarters and district personnel.

The pavement design engineers then design appropriate rehabilitation actions (overlays) for the previously selected projects. If necessary, detailed field investigations are made by the engineers before an overlay design is selected for each project. Several procedures are used by the engineers in designing an overlay, including AASHO method, deflection method, and use of the computer program SOMSAC developed in the first phase of the PMS study.

Interfacing of the NOS with Existing Procedures. It is proposed that the NOS replace the sufficiency portion of the priority rating system.

Results of the NOS can be used directly to select pavements for rehabilitation. The type of rehabilitation action is also identified by the results of the NOS.

It should be emphasized that the NOS cannot make final decisions of appropriate rehabilitation actions; such decisions can only be made by the ADOT management. The results of the NOS provide useful information and guidelines for selecting an appropriate rehabilitation action for pavements in a given condition state. However, such results should be supplemented by site-specific investigations and sound engineering judgments.

The NOS analyzes the highway network on a mile-by-mile basis. Design engineers are responsible for combining adjacent miles to form a project of practical size and selecting a single rehabilitation action for the project. The NOS selects the same rehabilitation action for all pavements in the same condition state. Since miles of pavements constructed as one project would be expected to perform similarly and hence would belong to the same condition state, a single rehabilitation action would be optimum for all miles in a project most of the time. In some situations, however, it is possible that different miles in a project perform differently and belong to different condition states. The NOS may select different actions for miles in different condition states. As an extreme (and unusual) example, suppose that a project consists of 4 miles in different condition states. Let us say the NOS selects ACFC for the first mile, 1-inch overlay plus ACFC for the second mile, ACFC plus heater scarifier for the third mile, and seal coat for the fourth mile.

The traditional approach to this situation would be to select the dominant action that would correct the most severe condition. However, such a decision would not be the most cost-effective for each individual mile, and thus would not be optimum for the total 4-mile project. It is hoped that the designer considers alternate treatments for each mile insofar as it is practical to do so.

In some situations such as the previous example, an action or combination of actions may not meet the optimum cost requirements. The designer should try to stay within 10 percent of the total cost assigned to the project by the NOS. More specifically, the total cost for an aggregation of projects should not exceed that allocated by the NOS.

For the NOS to work properly and consistently, the actual rehabilitation actions selected by the design engineer should not differ significantly from the optimum actions identified by the NOS except for a small number of cases in which exceptional field conditions are observed. For most cases (at least 80 percent of the time), the optimum action identified by the NOS should be responsive to the deficiencies of the pavement as determined by the engineer through site-specific investigation. If an action different from the recommended action is selected, justification should be provided.

If the optimum actions selected by the NOS do not conform to the judgment of the design engineer in a significant number of cases (greater than 20 percent of the total), adjustments in the NOS would be clearly warranted.

If specific actions are considered inappropriate by the design engineer for given condition states, such actions should be specified as being infeasible. The program will eliminate infeasible actions from its search for the optimum action and select some other action as being optimum.

In the event that the NOS produces impractical or otherwise unacceptable rehabilitation actions, it may be necessary to make more complex adjustments to the program. The most likely adjustment would have to do with the prediction models of pavement performance.

Monitoring of the NOS

The components of the NOS that should be monitored include costs, transition probabilities, and current network condition.

<u>Monitoring of Costs</u>. It will be necessary to maintain up to date data for both annual routine maintenance and construction costs. In order to obtain routine maintenance costs a sample of roads in each condition state should be selected and average annual costs recorded. Information of this type should be available from the ADOT maintenance management records stored in the PECOS system. Construction costs of various rehabilitation actions can be obtained from contract records. If costs of all rehabilitation actions increase by the same amount (due to inflation), the selection of the optimum action would not be significantly affected although budget requirements would be increased. A convenient form for recording cost data is shown in Table 10.

<u>Monitoring of Transition Probabilities</u>. The transition probabilities, $p_{ij}(a_k)$, can be interpreted as the proportion of roads in condition i that move to condition state j in 1-year if the k^{th} rehabilitation action is applied. For the present study, the transition probabilities were calculated from regression equations derived from a sample of pavement performance data. As more data become available, the reliability of the transition probabilities should be checked against the observed performance of roads.

All the roads on which pavement performance data are measured should be used in the verification of the transition probabilities. A convenient form for recording verification data is shown in Table 11. This form should be used for each rehabilitation action.

The reliability of the transition probabilities calculated from recorded data should increase as more and more data become available. If significant differences between calculated and assumed values of transition probabilities are found, revisions to the assumed values should be made. Since transition probabilities are inputs to the computer programs, changes in the probabilities can be readily made without having to change the programs themselves.

Table 10. FORM FOR MONITORING COST INPUTS

Condition State	Rehabilitation Action	Sample Size (Number of Miles)	Routine Maintenance Cost		Construction Cost	
			Observed Average	Estimated	Observed Average	Estimated

Table 11. FORM FOR MONITORING TRANSITION PROBABILITIES

		Condition State j					
		1	2	...	j	...	
Condition State i	1						
	2						
	⋮						
	j				No of Miles = (n_{ij}) Observed Proportion = $\frac{(n_{ij})}{N_i}$ Estimated Proportion = ($p_{ij}(a_k)$)		$N_i = \sum_j n_{ij}$
	⋮						

Monitoring of Current Network Condition. Results of the NOS provide estimates of proportions of roads expected to be in different condition states at the beginning of each time period. At the end of a given period, actual conditions of roads would be available from the annual pavement condition survey. The observed proportions of roads in different condition states can be found from the survey data. If the NOS is working properly, a reasonable agreement between the observed and the estimated proportions of roads in different condition states should be found.

Of particular significance are the proportions of roads in acceptable and unacceptable condition states. The observed proportions in these condition states should satisfy the performance standards specified for the system. This can be monitored by preparing performance graphs similar to those shown in Figure 3. Comparison of pavement performance and cost over time (as shown in Figure 3) would be a useful tool in evaluating how well the rehabilitation policies are working.

Staffing Requirements for Statewide Implementation of the NOS

Staffing requirements for using the NOS to set rehabilitation policies and to prepare rehabilitation budgets and for monitoring and updating the NOS are discussed in this section. Staff required for other related activities such as pavement condition surveys and maintenance of PMIS data base are not included in the estimates of personnel discussed below.

It is suggested that a 4-person staff be assigned for the use and maintenance of the NOS on a statewide basis. The staff should consist of a senior highway engineer in charge of maintaining the NOS, one assistant engineer, and two staff engineers.

The person in charge of the NOS should be an experienced highway engineer who is thoroughly familiar with the ADOT's existing procedures of establishing pavement rehabilitation policies and preparing rehabilitation budgets. This person should also have a strong background in engineering research projects involving analytical modeling. Responsibilities should include overall supervision of the routine use and monitoring of the NOS and coordination with managerial personnel in design, materials, priority programming, and field operations.

The assistant engineer should have a strong background in statistical and probabilistic procedures and some knowledge of operations research techniques. The responsibilities of such a person should include collection and organization of input data for the NOS; monitoring costs, transition probabilities, and current network conditions; and updating and modifying various components of the NOS as necessary.

At least one of the staff engineers should have a strong background in computer programming. Both the staff engineers should assist in preparing summaries of results of the NOS and making changes in the input data as necessary.

The staff would be expected to interact with other groups involved in the decisions of pavement rehabilitation, including design engineers, materials engineers, priority programming staff, district engineers, and field supervisors.

Use of the NOS on a Routine Basis

Once the trial implementation of the NOS is completed (probably over a period of 2 to 3 years) and confidence in the reliability of the results of the NOS is gained, the routine use of the NOS should begin. The two primary functions of the NOS will be:

- to prepare annual and long-term (5-year and 10-year) rehabilitation budgets

- to set rehabilitation policies.

Preparing Rehabilitation Budgets. Results of the NOS provide a set of optimum rehabilitation actions at various time periods for roads in different condition states and different road categories. These results can be used to calculate annual rehabilitation costs of all roads in each road category. By summing the costs over all road categories for a specified budget period (e.g., 5 years), the total rehabilitation budget required to maintain desired performance standards can be found.

Setting of Rehabilitation Policies. Ideally, the NOS programs would be run once and the results would be used to set short-term (e.g., over the next 5 years) as well as long-term (stationary) policies. The results of the NOS specify the optimum rehabilitation actions at various time periods for roads in various condition states for each road category (i.e., each traffic and region combination). The computer programs should be run for all road categories for desired performance standards.

An iterative procedure will be necessary to obtain a match between desired performance standards and total rehabilitation funds available over some period of time (such as 5 years). In such a procedure, the NOS programs are first run at an initial set of performance standards and the total expected cost of rehabilitation policies across all road categories is calculated for the period of interest. If the total cost is significantly different from the available funds, appropriate revisions in the performance standards are made, the programs are run again, and a new set of rehabilitation policies and corresponding costs is found. This procedure is repeated until a match between costs and available funds is obtained.

By combining the results of the NOS with the PMIS data base, it will be possible to specify optimum rehabilitation actions for pavements on a given route and between given mile-posts. Since the results of the NOS will be on a mile-by-mile basis, it will be necessary to combine appropriate miles to form projects. The design engineer may either specify a uniform action or a variable action over the length of a project based on site-specific investigations.

In practice, the NOS should be run once each year to assess whether the previously selected rehabilitation policies are still appropriate. If the observed performance of pavements is significantly different from the expected performance due to conditions such as unusually severe weather, changes in the previously selected policies may be necessary.

Each year after the pavement condition survey is completed, the reesults of the NOS should be monitored against observed network condition. Plots such as those shown in Figure 3 should be prepared to evaluate whether desired levels of pavement performance are achieved and whether overall rehabilitation costs are in close agreement with budgeted costs.

SUMMARY AND CONCLUSIONS

A network optimization system (NOS) has been developed to assist the ADOT establish the most cost-effective pavement rehabilitation policies. The NOS can be used to determine which rehabilitation policies will achieve prescribed performance standards at a minimum cost. This information can be used to prepare 1-year, 5-year, and 10-year pavement rehabilitation budgets to maintain prescribed performance standards. With an iterative procedure, the NOS can also be used to determine the highest performance standards that can be maintained with fixed budgets. These results can be used to allocate fixed pavement rehabilitation budgets for different roads in the state in a manner that provides the best possible value for the public dollar.

Performance standards for the NOS can be specified in terms of the minimum proportion of roads with acceptable ride indices and amount of cracking and the maximum proportion of roads with unacceptable ride indices or amount of cracking.

The main steps involved in the NOS are: (1) generation of feasible alternative rehabilitation policies, (2) prediction of future performance of the highway network and the total cost under alternative policies, and (3) determination of the minimum cost policy. Models for predicting future pavement performance under various rehabilitation actions were developed from a regression analysis of real data obtained from pavement condition measures. The prediction models were subsequently verified by the ADOT against an independent data set and were found to agree well with the data.

A complete set of computer programs was developed to facilitate implementation of the NOS by the ADOT. These computer programs were tested and debugged on the ADOT computer facilities with both hypothetical and real examples.

Results of the illustrative examples show that the NOS is ready for implementation by the ADOT. The potential advantages of implementing the NOS include the following.

- The NOS will permit the most efficient use of limited funds in maintaining desired performance standards for the pavements in the state. This may allow management to maintain current standards at a lower cost or to maintain higher standards with the current budget.
- The NOS will help maintain a uniform and consistent rehabilitation policy over a long period of time. This means that for pavements in a given state at any time, the same rehabilitation action would be optimum. In addition, the proportion of roads in good, fair, or poor condition will remain stationary over time if the policies selected by the NOS are implemented.
- In the NOS, decisions about rehabilitation actions are based on the most current information about the condition of various pavements in the network. This information will be available from the annual pavement condition surveys. Thus, if some pavements do not perform as expected, the NOS will take this into account and select rehabilitation actions appropriate for the observed condition rather than the expected condition.
- The NOS will permit monitoring of the predicted system performance and cost against the observed performance and cost. It will be possible, therefore, to check whether the management

goals with regard to pavement performance of the network are being satisfied.

- The NOS will enable the ADOT management to estimate consequences of significant changes in pavement rehabilitation budgets. For example, in the event of large budget cuts, the reduction in the pavement performance standards of the network can be estimated.