Analysis of Arizona Department of Transportation's New Pavement Network Optimization System

KELVIN C. P. WANG, JOHN ZANIEWSKI, AND JAMES DELTON

The award-winning network optimization system (NOS) has been revised, improved, and implemented in an advanced 32-bit microcomputer environment in the Arizona Department of Transportation (ADOT) for more than 1 year. The new NOS is named AZNOS, which stands for Arizona Network Optimization System. NOS has been the primary instrument used by ADOT in planning its highway preservation program since 1980. An analysis of the microcomputer implementation in the 32-bit operating environment by using a newly developed linear optimizer, NOSLIP, is presented. The desktop AZNOS encourages use of the model for extensive sensitivity analysis and testing. The sensitivity analysis and sample runs of the new AZNOS are demonstrated. The results show that the budgetary requirements from steady-state runs should not be used for an actual highway preservation program. Instead, a *pseudo-steady state*, when the budget based on AZNOS multiperiod runs stabilizes after a transition period, is used for budget planning. Rules to set up an infeasible action list were also established to improve the effectiveness of the model. Finally, discussions were made to demonstrate how ADOT management, engineers, and university faculty teamed up to apply true optimization techniques in solving real-world pavement management problems.

Extensive research has been conducted in the last 20 years in the area of network-level pavement management systems (PMSs). The methodologies used in PMSs have been evolving along with the advancement of new technologies in computer science and mathematical modeling. In the early 1980s a major PMS development occurred in the Arizona Department of Transportation (ADOT). It represented the pioneering efforts of applying operations research techniques in PMSs (*1*). The system methodology used in ADOT PMS is called the Network Optimization System (NOS). It uses a Markov process to define the transitions of pavement conditions and a linear programming model to minimize the total agency cost and maintain the highway network at specified standards for a multiyear horizon. An estimated $40 million was saved for the state of Arizona from 1980 to 1985 (*2,3*). Subsequently, a national Management Science Achievement award was awarded to ADOT (*3*). The basic model of NOS has been used by the Alaska Department of Transportation (DOT), the Kansas DOT (*4*), Finland (*5*), and Saudi Arabia (*6*). For more than 10 years the highway preservation program based on these answers from NOS has been providing ADOT management, the state transportation board, and the state legislature information on the needs of the state highway system.

However, the original NOS was implemented on a mainframe computer and required the user to lease a proprietary optimization program on a monthly basis. In addition to the pavement engineering staff required to run NOS, extra manpower in the information system group had to be dedicated to maintaining and updating the data base and programs. The user interface of the original development is archaic by today's standards. Since the initial implementation of NOS on a mainframe computer in 1980, technological advancement in microcomputer and problem-solving know-how have provided tremendous opportunities and insights into improving the PMS.

Therefore, enhancing the system, improving its accessibility, and simplifying its use should help more pavement engineers to use optimization techniques in their highway preservation programs. In 1991 ADOT management decided to implement enhancements to the NOS in the microcomputer environment.

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

The output of NOS enables ADOT management to determine

- The proportion of the pavements in each road category that will be expected to be in various condition states at the beginning of each time period, and
- The expected annual costs of pavement rehabilitation and routine maintenance.

The specific form of a rehabilitation policy is in terms of the proportion of roads of a given category in a condition state i to which a specified rehabilitation action k is applied at the l time period. The proportion can be interpreted as the probability that a given pavement would be in state i at time l and action k is taken.

Let $w^l_{i,k}$ denote the proportion of roads of a given road category that are in condition state i at the beginning of lth time period of horizon T and to which kth preservation action is applied. $w^l_{i,k}$ is time dependent and reflects the behavior of the system in response to selected rehabilitation strategies. $w_{i,k}$ reflects the steady-state condition of the system under a fixed level of funding for rehabilitation and is therefore time independent. The $w^l_{i,k}$ and $w_{i,k}$ are the two key variables in the process of setting up the short-term and long-term (steady-state) highway preservation policies. On the basis of the transition matrices and other constraints $w^l_{i,k}$ and $w_{i,k}$ can be determined through the linear programming process.

K.C.P. Wang, University of Arkansas, Fayetteville, Ark. 72701. J. Zaniewski, Department of Civil Engineering, Arizona State University, Tempe, Ariz. 85287. J. Delton, Arizona Department of Transportation, 1221 North 21st Avenue, Phoenix, Ariz. 85009.

REVISIONS OF NOS

NOS is an effective financial planning tool for pavement preservation programs on the basis of the relatively small amount of current pavement information. Only roughness and cracking information on existing pavement is needed to conduct NOS runs. In addition, the capability of conducting long-term pavement financial analyses and providing reliable information are the important driving forces for ADOT to continue relying on this important tool for the preservation program.

The mathematical model of NOS is sophisticated and includes two major operations research techniques, Markov process and linear programming. A mathematical model is intended to be a representation of the real problem in the major areas of concern. Approximations and simplifications are generally required for the model to be effective and tractable. In addition, there must be a reasonably good correlation between the performance prediction and what would actually happen in the future. On the basis of the experience in the use of and examination of the mainframe-based NOS, a comprehensive analysis of the current system was conducted in 1992. Subsequent revisions and improvements were made to the system as documented previously (*7*), resulting in an enhanced, microcomputer-based AZNOS, which stands for the Arizona Network Optimization System (*8*).

Because of the computation intensity and memory requirement of AZNOS, it was hosted in a 50-MHz 486 computer with 24 megabytes of RAM. The IBM OS/2 2.X was selected as the operating system because of its 32-bit flat memory model capability and excellent DOS and Windows compatibility with existing ADOT PMS data bases. In addition, a native 32-bit OS/2-based linear optimizer, NOSLIP, was developed for the implementation of the system.

It was revealed in this study that the factor of crack change is not significant in determining the acceleration of pavement deterioration in Arizona. Therefore, this factor was removed from the system. A new structure of pavement condition states was set up for the optimization model. The number of condition states was reduced from 120 to 45 because of the removal of the cracking change factor. The number of rehabilitation actions was reduced from 17 to 6 on the basis of the discovery that a number of rehabilitation actions were redundant. The six new actions are as follows:

1. Routine maintenance,
2. Seal coat,
3. ACFC, ACSC (asphalt concrete surface course),
4. ACFC + AR (asphalt rubber), ARAC (asphalt rubber + asphalt concrete),
5. 2-in. (5.1-cm) AC (asphalt concrete) + AR, 3-in. (7.6-cm) AC + FC (friction course), and
6. 4.5-in. (11.4-cm) AC + FC and other heavier actions.

In addition, new level boundaries for both roughness and cracking were redefined to reflect today's engineering practice. New transition probability matrices (TPMs) were established for both the Interstates and non-Interstates on the basis of the 13-year pavement performance data base in Arizona. The TPMs were modified with accessibility rules to improve the prediction of pavement behavior. Two approaches were used to evaluate the TPMs in the study. First, the current pavement performance data base was used to develop new TPMs. Second, the Chapman-Kolmogorov method was used to examine the logical extension of the transition probability matrices from a single step to the long-term pavement behavior.

As a result the concept of pavement probabilistic behavior curve (PBC) is established on the basis of the Chapman-Kolmogorov equations (*9*). Figure 1 demonstrates a set of PBCs for the region of high-traffic, desert Interstates. It can be seen from Figure 1 that the proportion of pavements remaining in the best condition state (low levels of cracking and roughness) after 20 years of service is approximately 5 percent. The curves of *best ride* (low roughness only) and *worst ride* (low cracking only) demonstrate the rapid deterioration of riding quality over time consistently.

AZNOS SAMPLE RUNS AND ANALYSIS

AZNOS is capable of conducting the steady-state and multiperiod runs in either batch or single mode. In the 50-MHz 486 computer a steady-state run usually takes less than 15 sec. For a 5-year multi-

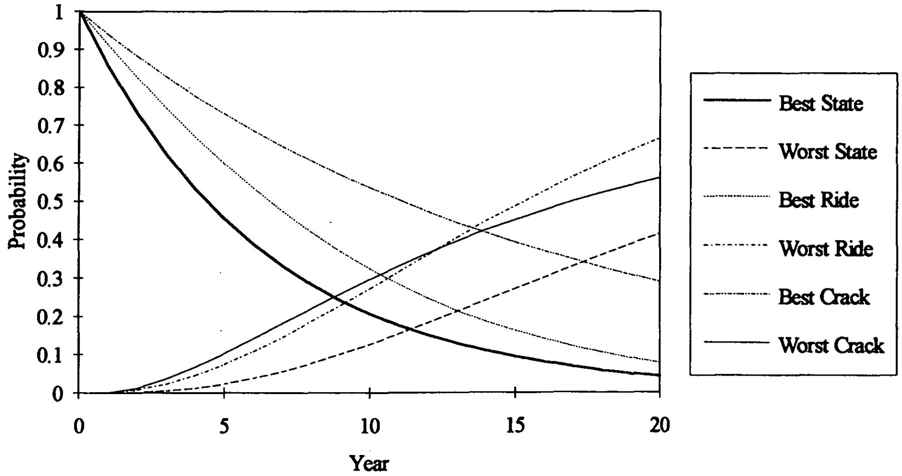


FIGURE 1 Pavement PBCs under routine maintenance after new construction, high-traffic road category of Interstates in desert region.

period run it takes from 3 to 10 min to run mostly depending on the setup of infeasible actions, the tolerance on the performance standards, and how multiple tasks in OS/2 are scheduled. The user time required on a microcomputer is much lower than that on a mainframe computer in ADOT, where it usually takes 30 min or more to get an output of a multiperiod run. Figure 2 is an example of actual AZNOS output from a NOSLIP multiperiod run for the high-traffic, desert region Interstates. The first portion of the output contains a description of the problem and its aggregate results, including the parameters used in the optimization and the optimized cost. The second portion contains the performance standards and achieved standards for each year. The summary of the AZNOS-recommended annual budget for each year of the planning horizon is also shown in Figure 2. One page is used for the detailed AZNOS budget recommendation, which is not shown in Figure 2.

Selection of Infeasible Actions

The introduction of infeasible actions was based on the finding in the original NOS development that low-level surface applications, such as asphalt concrete friction course (ACFC), were selected a disproportionate amount of the time. The selection of infeasible actions for certain condition states should be based on engineering judgment because there are no mechanistic procedures to determine the selection. However, on the basis of numerous runs conducted during this research, the rules for the selection of infeasible actions for AZNOS can be generalized as follows:

1. Routine maintenance should be feasible for all condition states. For pavements in very poor condition states, it provides AZNOS the ability to defer rehabilitation action;
2. All actions should be feasible for pavements in the best condition state. When high pavement condition standards are needed, portions of the pavements in the best condition state may need structural overlay to keep the whole network in pristine condition;
3. More than one action should be feasible for pavements in any condition state. This provides different alternatives that AZNOS can choose to achieve cost minimization; and
4. Low-cost rehabilitation actions, excluding routine maintenance, are not used for pavements in very poor condition states, such as pavements in the worst condition state with high roughness and cracking levels.

Steady-State, Multiperiod, and Performance Standard

The solution from steady-state runs represents the uniform rehabilitation strategy to keep the pavement network at required condition level. The proportion of pavements in each condition state becomes constant, and the necessary rehabilitation actions for pavements in any condition state are fixed for every year. The solution from steady-state AZNOS runs could provide important information about long-term pavement behavior and corresponding budgetary needs. Pavement steady-state rehabilitation policy is independent of time, and the actual pavement condition data at any time are irrelevant.

An observation based on the AZNOS runs is that the budget needs from steady-state runs are substantially higher than those from multiperiod runs. This observation is different from the information presented in the original NOS development, which shows that the budget requirement for steady state is less than that for the periods before the steady state. Because there are no demonstrations that budget levels from steady state must be lower than the ones from multiperiod runs, when the pavement condition standards are the same, it cannot be concluded that the relationship between steady-state budget and multiperiod budget presented in the original NOS development (*1*) are universally true. In fact, the steady-state model originally formulated only seeks to determine the budget and actions required to keep the pavement network in a constant condition with a repeated set of actions. It does not seek to determine the minimum budget required to maintain the steady-state condition when the current pavement conditions are known.

A hypothetical example can be used to explain why a budget based on steady-state runs can be higher than that based on multiperiod runs. Assume that a 100-mi (160.9-km) highway system was built 5 mi at a time each year. The design life of each section was 20 years and reconstruction was required at the end of the design life if no rehabilitation action was taken before reaching the design life. It is also assumed that pavement performances of all the 20 5-mi (8-km) sections were identical. Two rehabilitation policies could be used. The first was the steady-state policy that mandates reconstruction of a 5-mi section at the end of its design life at a cost of \$16/yd^2 (\$19/m^2). Therefore, steady state was achieved after 20 years of the construction of the first section of pavements. The second policy is to maintain the system at the same performance levels as in the steady state, but to rehabilitate any place of the system at the necessary time. Therefore, rehabilitation maintenance action of a 2-in. (5.1-cm) structural overlay can be used at a cost of \$6/yd^2 (\$7.2/m^2). The resulting budget from this multiperiod policy will be well below the budget determined by the steady-state run.

Therefore, the network steady state may never be achieved because the budgetary requirement can be too stringent to be met. In practice, steady-state results can be used as engineering references only. The budgetary recommendations of a 10-year AZNOS run is shown below for a high-traffic, desert region of Interstate highways:

Y-1	*Y-2*	*Y-3*	*Y-4*	*Y-5*	*Y-6*	*Y-7*	*Y-8*	*Y-9*	*Y-10*	Total
\$9.6	\$18.0	\$22.4	\$22.1	\$22.4	\$22.8	\$23.2	\$23.5	\$23.8	\$24.1	\$211.9

The network arrived at the performance standards at the third year. From Year 3 to Year 10 the budget need for each year was about \$22 million to \$24 million. Therefore, the network can be considered stabilized and a pseudo-steady state was achieved at Year 3. The mathematical model for the pseudo-steady state is shown in the following:

The objective:

$$\text{Minimize} \sum_{l=1}^{T} \sum_{i,k} w_{i,k}^{l} \cdot d_l \cdot c(i,k) \tag{1}$$

Subject to

$$\sum_{k} w_{j,k}^{l} = \sum_{i,k} w_{i,k}^{l-1} \cdot P_{ij}(a_k), \text{ for } 1 < l \leq T \tag{2}$$

$$\sum_{k} w_{i,k}^{l} = q_i \tag{3}$$

$$\sum_{i} \sum_{k} w_{i,k}^{l} = 1 \text{ for all } l = 1, 2, \ldots, T \tag{4}$$

```
*===========================================================*
         AZNOS MULIT-PERIOD RUN FOR 5-YEAR HORIZON
           (Based on TPM:kw31i.dat and Actual Costs)
     AUTHOR: KELVIN C.P. WANG, PAVEMENT MANAGEMENT BRANCH
         ARIZONA DEPARTMENT OF TRANSPORTATION, 1992
*===========================================================*
  PARAMETERS & OPTIMIZED COST FROM THE LINEAR OPTIMIZER
____________________________________________________________
  Reading & Generation of Data: 0.05 min;
  Program Started at Tue Oct 20 14:46:11 1992
  Optimization Time:  8.82 min
  Phase 1 & 2 Iterations:  275, 513;
  Convergence Factors: 1.0E-06, 1.0E-06
  LP Variables:1200 & Constraints:280;m1=10,m2=10,m3=260
  Total Area of the Road Category    = 20082774 SY (16791757 SM)
  Unit Cost(Square Yard) for 5 Years = $4.653
  Recommended Budget for 5 Years     = $93.436 Million
____________________________________________________________
    CURRENT CONDITION TABLES BY HIGH & LOW LEVELS
____________________________________________________________
  --- Roughness(new Mays) ---      -----  Cracking(%)  ----
    LOW LEVEL    HIGH LEVEL         LOW LEVEL    HIGH LEVEL
     (<75)        (>105)             (<6)          (>12)
____________________________________________________________
     0.832         0.026             0.756         0.077
____________________________________________________________
     PAVEMENT PERFORMANCE TABLE FOR THE MULTI-PERIOD RUN
             (The Multiplier Factor, mf, is 0.95)
____________________________________________________________
 Year  ------- Roughness -------  ------- Cracking  -----
           Target    Achieved           Target    Achieved
____________________________________________________________
   2  Low   0.857,    0.857              0.731,    0.817
   2  High  0.073,    0.024              0.073,    0.038
------------------------------------------------------------
   3  Low   0.902,    0.902              0.770,    0.821
   3  High  0.069,    0.007              0.069,    0.026
------------------------------------------------------------
   4  Low   0.950,    0.950              0.810,    0.898
   4  High  0.066,    0.000              0.066,    0.014
------------------------------------------------------------
   5  Low   0.950,    0.950              0.810,    0.902
   5  High  0.066,    0.000              0.066,    0.013
------------------------------------------------------------
   6  Low   0.950,    0.950              0.810,    0.909
   6  High  0.066,    0.000              0.066,    0.013
____________________________________________________________
                  RECOMMENDED ANNUAL EXPENDITURE
                           ($Million)
___________________________________________________________
   Action  1       2       3       4       5       6    Total
Year
___________________________________________________________
 1       1.942   1.461   3.838  0.000   4.809   0.000  12.050
 2       1.971   0.384   5.426  0.000   0.105   3.996  11.882
 3       0.891  10.923   9.592  0.000   2.352   0.164  23.923
 4       0.784  13.199   8.483  0.000   0.119   0.000  22.585
 5       0.687  15.346   6.851  0.000   0.112   0.000  22.996
___________________________________________________________
Total    6.276  41.312  34.190  0.000   7.498   4.160  93.436
____________________________________________________________
```

FIGURE 2 AZNOS output of a 5-year multiperiod run for high-traffic, desert region Interstates.

$$\sum_{j,k} w^l_{j,k} \leq P_1\,(l) \cdot \gamma_i, \text{ for } i \in I, j \in j_1(i), 2 \leq l \leq T \tag{5}$$

$$\sum_{j,k} w^l_{j,k} \geq p_2(l) \cdot \epsilon_i, \text{ for } i \in I, j \in j_2(i), 2 \leq l \leq T \tag{6}$$

$$w^l_{j,k} \geq 0, \text{ for all } j,k, \text{ and } 1 \leq l \leq T \tag{7}$$

where

$w^l_{i,k}$ = proportion of roads of a given road category at lth time period that are in condition state i and to which kth preservation action is applied,
I, T = complete set of condition states and total number of analysis periods,
d_l = present worth of $1 spent during lth time period,
$c(i,k)$ = cost matrix of action k for pavements at condition i,
q_i = current proportion of roads in ith condition state,
γ_i = maximum proportion of roads in the set of undesirable states denoted by $j_1(\mathrm{i})$,
$j_1(\mathrm{i})$ = the set of number specifications of undesirable states,
ϵ_i = minimum proportion of roads in the set of desirable states denoted by $j_2(i)$,
$j_2(i)$ = the set of number specifications of desirable states, and
$p_1(l)$ and $p_2(l)$ = two multipliers, ≥ 1 and ≤ 1, to permit a higher than γ_i proportion of roads and a less than ϵ_i proportion of roads in undesirable and desirable states at the lth time period, respectively.

Another observation is that the budget requirement based on AZNOS is higher than that based on the old NOS. The deterioration of pavements under routine maintenance based on the new TPMs is much faster than that based on the old TPMs. There are three major reasons for this discrepancy. First, the new TPMs were based on actual pavement performance data. Because experience indicates that the real budget needs for the ADOT highway preservation program were frequently higher than the recommended budget levels based on the old TPMs, the old TPMs were thus overoptimistic on pavement performance. Second, accessibility rules were applied for the new TPMs, which eliminate the possibilities that a pavement can transition to a better condition state under routine maintenance. It resulted in higher probabilities for pavements to transition to poorer pavements than the probabilities from the old TPMs. Third, the analysis run based on the new TPMs used more stringent classifications of roughness and cracking levels and thus higher performance standards than the mainframe runs. Therefore, the required budget levels based on AZNOS are higher than the budget levels determined by the original mainframe-based NOS.

On the basis of the AZNOS runs the relationship between budget needs and performance standards was revealed. It can be illustrated by an example of both steady-state and 4-year multiperiod runs based on a high-traffic, desert region of Interstates as shown in Figure 3. Because the standard of low-level roughness is usually the critical factor it was used in the example. A range of the roughness standards from 0.900 to 0.990 with an increment of 0.005 was used. The relationships of budget and roughness standard are different for the steady-state run and the multiperiod run in this example. The budget needs for the steady-state run increase rapidly when the roughness standard passes 0.940, whereas the budget needs for the last year of the multiperiod run increase steadily along with the increasing standard. In addition, the budget needs based on steady-state runs were consistently higher than those based on multiperiod runs throughout the entire roughness range. When the standard was set to be 99 percent of the pavements with a low roughness level as shown in Figure 3, the budget to meet the standard became $120 million for the steady-state run and about $35 million for the fourth year of the multiperiod run. To meet this stringent standard of steady state, almost all of the pavements in the network need structural overlays every year. However, many fewer pavements need overlays if decisions are made on the basis of the multiperiod run.

AZNOS SENSITIVITY ANALYSIS

Structural improvements were made to the NOS model as described elsewhere (*9*). As a result because of the much more stringent new levels of classifying pavement condition states, the preservation program requires much higher budget expenditures by using the existing pavement condition standards. Therefore, it is necessary that

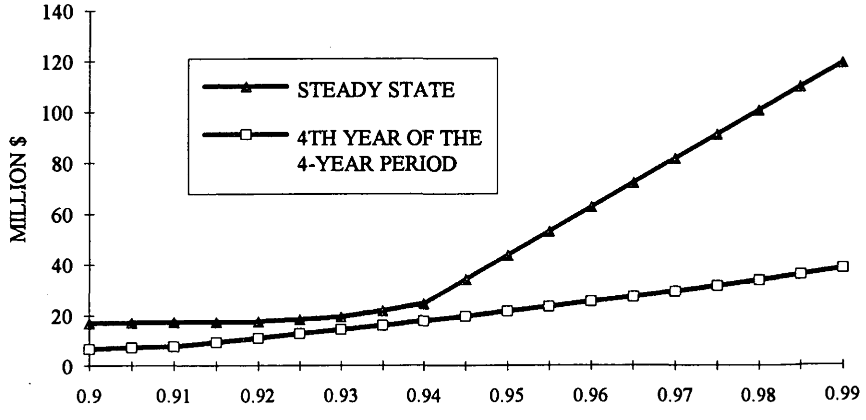


FIGURE 3 Relationship between budget needs and roughness standard on the basis of steady-state and multiperiod runs for high-traffic, desert region Interstates.

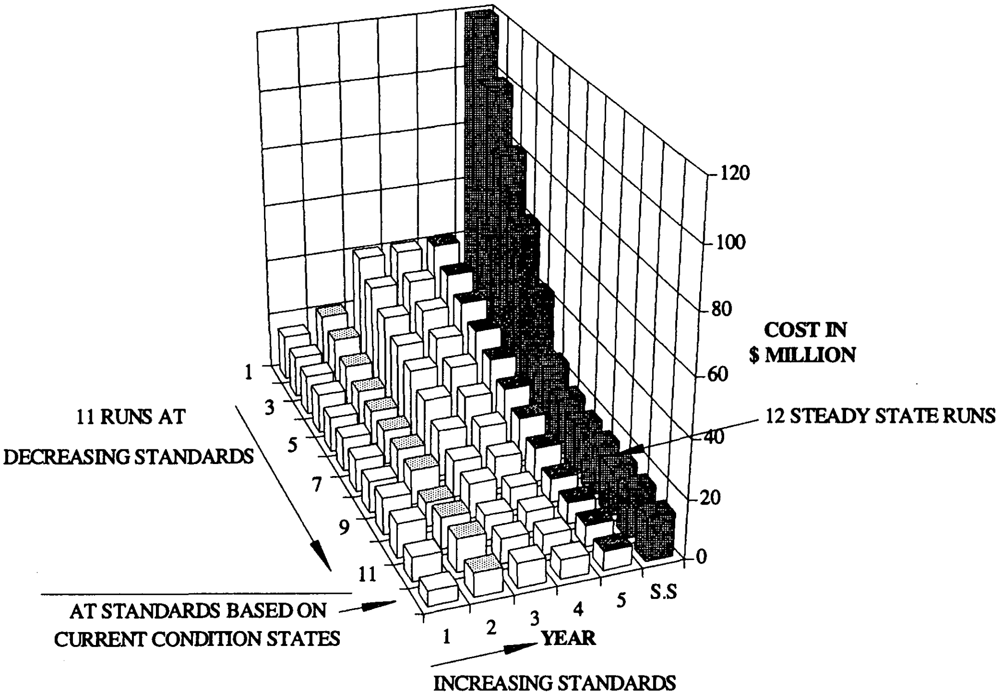


FIGURE 4 Sensitivity analysis chart for high-traffic, desert region Interstates.

a set of new pavement condition standards be determined on the basis of the modifications and the possible budget program. In addition, to validate the model and examine the sensitivities of its parameters, variations of the standards need to be tested against the corresponding budgetary requirements.

The starting point to set up the ranges of performance standards is the present pavement condition. The original performance standards were used for the high end of the sensitivity testing range. A total of 11 runs were conducted for each of the five road categories by using a decreasing standard between each run. A 12th run was conducted by using the existing pavement condition states as the standard for the corresponding road category. The low roughness levels in most AZNOS runs were the critical factors; thus, it was used in all sensitivity analyses.

Because the high-traffic, desert region of Interstates has the largest pavement area in Arizona, it was selected to demonstrate the sensitivity analysis here. Steady-state and multiperiod runs are shown in Figure 4. The vertical axis represents the required budget, in millions of dollars. A 5-year horizon was assumed in all the multiperiod runs. The x-axis represents the year number of the AZNOS runs. The y-axis represents AZNOS run numbers. It should be noted that a special range of roughness standards from 0.90 to 0.99 was used for this road category for the purpose of illustration. The roughness standards for the high-traffic, desert region of Interstates are highlighted in Figure 5. The vertical axis of Figure 5 is the percentage of pavements with a low roughness level. In addition, it was assumed that the pavements of Interstates arrive at standards at Year 3.

Total budget needs for Interstates are shown in Figure 6. The multiplier factor of 0.95 was used for all the multiperiod runs so that lower standards could be used for the interim years to converge to the standards. Figure 6 shows that higher budget needs correspond to higher standards. It can be seen that the budget requirements for Interstate highways are evenly spread out throughout the 5-year horizon for 12 runs. In addition, as discussed previously, budget requirements for steady-state runs are consistently higher than those for multiperiod runs, as shown in Figure 6.

NEW PAVEMENT CONDITION STANDARDS FOR ADOT

On the basis of the 12 AZNOS runs conducted for each road category for both steady-state and multiperiod runs, performance standards were determined, as shown in Table 1. The corresponding AZNOS runs were conducted, and the subsequent budget requirements for Interstate highways are shown in Figure 7. The total network budget is shown in Figure 8 for the fifth year of the planning horizon. The ADOT budget for 1991 was $60 million without considering the safety and other engineering costs, whereas the results from AZNOS show that at the fifth year about $78 million is needed for the pavement network to meet the new standards.

ACHIEVED RESEARCH GOALS

Improvements were made to the ADOT NOS in this study, resulting in the 32-bit microcomputer-based AZNOS. New tools were provided for the analysis of pavement long-term behavior on the basis of the Chapman-Kolmogorov equations. Extensive sensitivity analysis was conducted on the newly developed AZNOS to validate the implementation and set up new pavement condition standards for ADOT. It was revealed in that sensitivity analysis that the budget needs based on steady-state runs are not necessarily less than those based on multiperiod runs. Because it required fewer resources to keep the network at the standards when the solutions

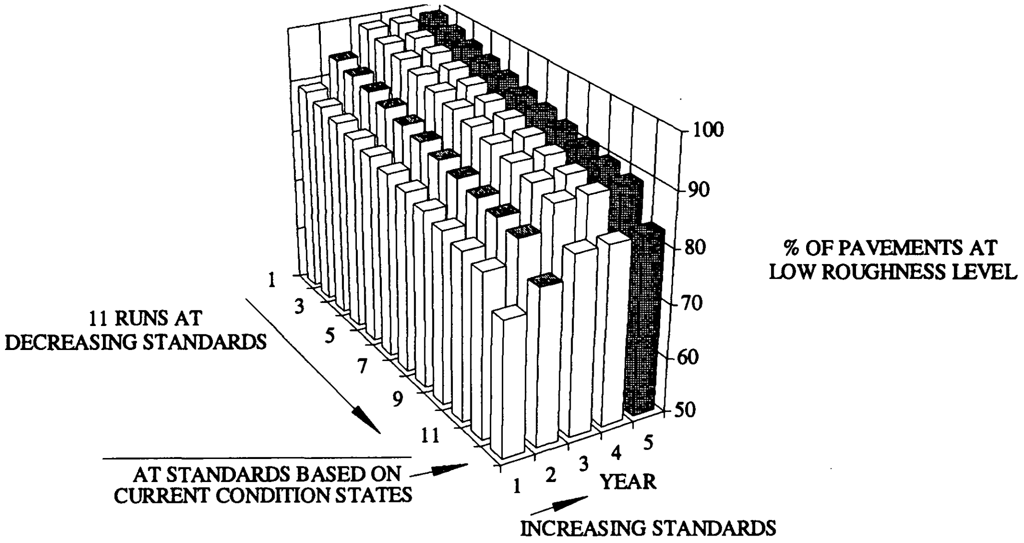


FIGURE 5 Standards of low roughness level for sensitivity analysis for high-traffic, desert region Interstates.

from multiperiod were used, it was recommended that steady-state results not be used for actual pavement preservation program.

On the basis of the results of the present study it was concluded that AZNOS multiperiod runs should be used in an actual pavement preservation program. The ideal situation represented by solutions from steady-state runs is not practical. On the basis of the Chapman-Kolmogorov equations, a methodology was developed for the analysis of long-term pavement behavior by using PBC.

The newly developed 32-bit linear optimizer NOSLIP was used as the optimizer for AZNOS. Very few numerical problems were met in testing and using NOSLIP with other sample problems. A few problems were encountered because of the use of the AZNOS input data instead of the optimizer. For instance, when certain rehabilitation actions were set to be infeasible, such as structural overlay for the best condition state, the optimizer may determine that the problem was infeasible. The reason for this is that when the standards were set very high structural rehabilitation action had to be applied to a portion of the pavements in the best condition to satisfy the standards. Therefore, all actions had to be available to pavements in the best condition state for the optimizer. The new system provides better user interface and lower consumption of user time. Batch run capabilities are also provided. The linear optimizer NOSLIP provides a much faster response time than the mainframe version. The newly developed, microcomputer-based AZNOS pro-

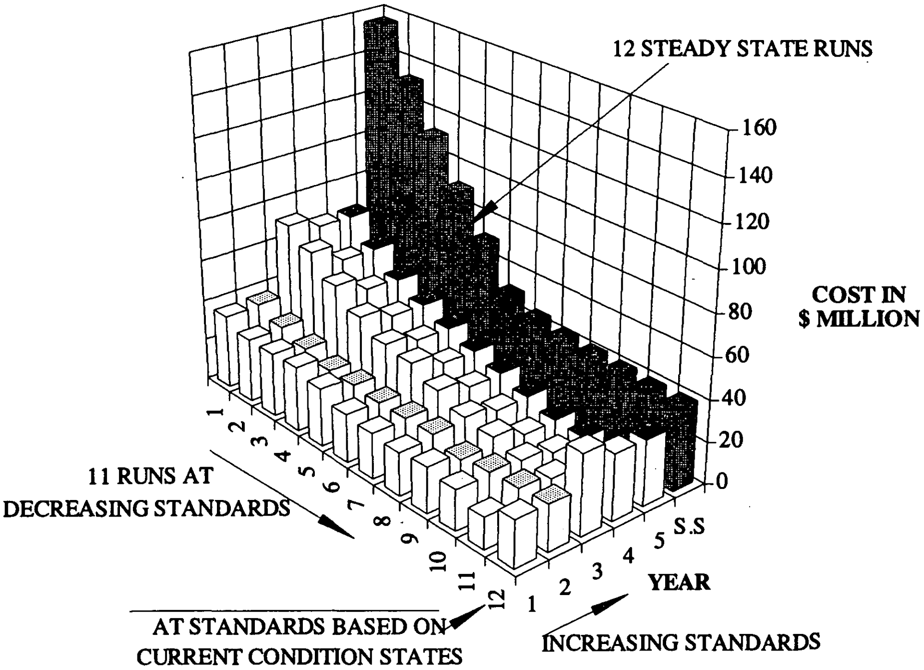


FIGURE 6 Sensitivity analysis chart of Interstate road categories.

TABLE 1 New Performance Standards for Highway Preservation Program of ADOT (Asphalt Concrete)

	TRAFFIC ADT	MIN. % MILES IN SATISFACTORY CONDITION	MAX. % OF MILES IN OBJECTIONABLE CONDITION
INTERSTATE	ROUGHNESS		
	0-2000	NOT APPLICABLE	NOT APPLICABLE
	2001-10,000	85	5
	10,001+	95	5
INTERSTATE	% CRACKING		
	0-2000	NOT APPLICABLE	NOT APPLICABLE
	2001-10,000	80	5
	10,000+	85	5
NON-INTERSTATE	ROUGHNESS		
	0-2000	45	25
	2001-10,000	70	10
	10,000+	80	10
NON-INTERSTATE	% CRACKING		
	0-2000	60	20
	2001-10,000	70	15
	10,000+	80	10

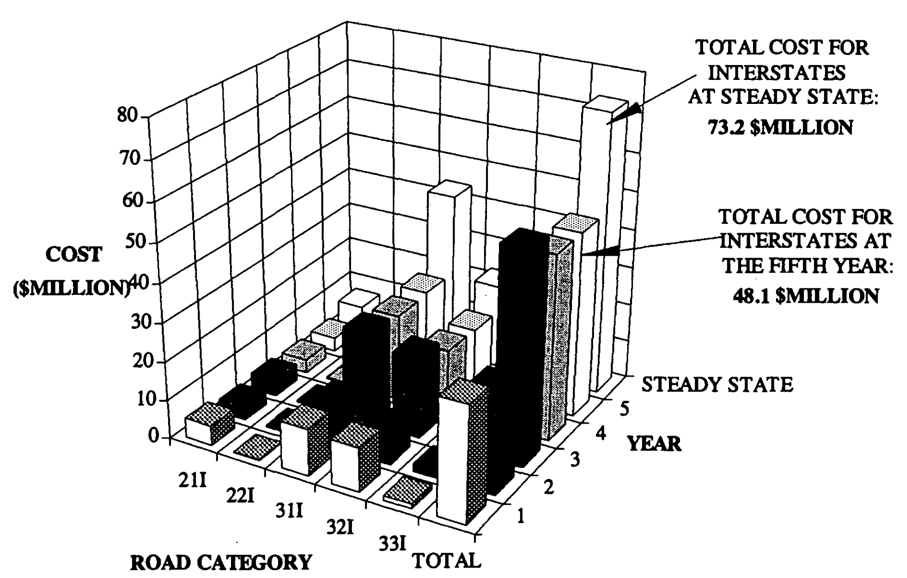
vides an enhanced PMS with improved accessibility and faster response time.

OPTIMUM SOLUTION, SATISFACTORY SOLUTION, AND PMS

In the past 15 years or so a number of institutions have been using techniques of optimization and stochastic process for their pavement preservation programs. Many of them were very successful. However, even larger numbers of agencies have continued using relatively simple PMS based on ranking, prioritization, or semioptimization techniques. Even though optimization provides powerful tools for minimizing agency costs or maximizing benefits, it requires PMS engineers to have a substantial quantitative background and the management and legislature to be supportive in adapting new systems. In addition, the quality of the prediction model and the input data basis will determine the accuracy of the output from the optimizer. Furthermore, the resources needed to develop an optimization-based PMS are substantially higher than those needed to develop a simple data base–based system.

However, NOS has been an important instrument in the ADOT pavement preservation program in the past 12 years. The development of the current annual budget relies heavily on the outputs from the multiperiod AZNOS runs. The continuing reliance on this PMS on the basis of optimization has saved taxpayers tens of millions of dollars in the past decade (*3*). The successful story of the Arizona PMS is the result of three combined efforts: management support, the pavement management engineer's capability of using new technologies and innovations to maintain and update the PMS data bases, and research efforts from the university faculty. This research project was another endeavor from the PMS engineer and the management that new advancements in both hardware and software were used for the enhancement of the existing system. Therefore, to succeed in using an optimization-based PMS, the application of optimization techniques for pavement management should be fully supported and understood by the management. In addition, improving the system by using new technologies must be vigorously pursued by the pavement management engineer.

It should be recognized that the solutions from the optimizer are optimal only with respect to the model being used. Because the model is an idealized instead of an exact interpretation of the real problem, there cannot be a guarantee that the optimal solution from the model will prove to be the best possible solution that could be implemented for the real problem. There are too many imponderables and uncertainties associated with the real problem. However, if the model is well formulated and tested, the resulting solution should be a good approximation of the real problem. Arizona's experience shows that the test for the practical success of an



TOTAL COST FOR INTERSTATES AT STEADY STATE: **73.2 $MILLION**

TOTAL COST FOR INTERSTATES AT THE FIFTH YEAR: **48.1 $MILLION**

FIGURE 7 Determination of standards for Interstate highways.

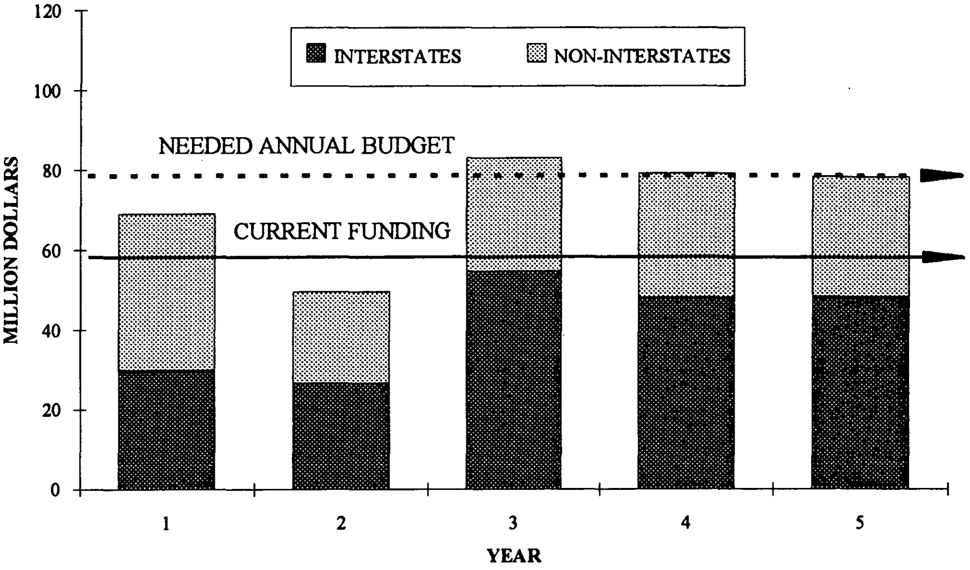


FIGURE 8 Network budget program for fifth year of 5-year planning horizon on the basis of multiperiod AZNOS runs.

optimization-based PMS should be whether the system provides a better guidance for the preservation program than can be obtained by other means. It is impossible to prove that AZNOS is the best possible tool. However, the tremendous savings achieved by the state through the use of true optimization techniques demonstrate that AZNOS is an excellent tool for determining the pavement preservation program's budget requirements.

H. Simon points out (*10*) that *satisficing* is much more prevalent than optimizing in an actual practice. He defines *satisficing* as a combination of *satisfactory* and *optimizing*. Simon describes the tendency of managers to seek a solution that is "good enough" for the problem at hand instead of develop an overall measure of performance to optimally reconcile conflicts between various objectives. The distinction between optimizing and satisficing reflects the difference between theory and the realities frequently faced by many PMS engineers in trying to implement that theory in practice.

FUTURE RESEARCH NEEDS

The application of Markov prediction models in PMS has provided an effective technique in pavement performance prediction. NOS and AZNOS require the infeasible action list as input data to improve the ability of AZNOS to choose cost-effective actions. The requirement that an infeasible action list be used relates directly to the prediction model structure, which needs further studies for possible improvement.

The steady-state model implies that steady-state solutions may recommend longer life actions that require less programming but more expensive projects. Fewer projects in the annual program can mean fewer user delay costs and possibly lower agency administrative costs. The quantification of these factors needs further study. In addition, NOS and AZNOS are not capable of establishing realistic pavement project locations because of the aggregate model structure. Efforts are under way in ADOT to integrate a Knowledge-Based Expert System to the existing PMS so that expert opinions can be stored in the computer to help determine candidate projects, including the locations and timings. Furthermore, sensitivity analyses of the Markov prediction models and their possible calibration are necessary and were never conducted before.

The successful realization of rehabilitation project selection and global optimization in the microcomputer environment will advance pavement network optimization to a new level of sophistication and maturity. A systems approach can be applied to the integration of financial planning, program planning, and pavement design into a single package within the framework of modular design and object-oriented programming. The modern 32-bit desktop operating systems provide tremendous opportunities for the integration of graphical data presentation and query, geographical information systems, and multimedia capabilities along with the existing optimization module into a comprehensive pavement information system in computer networks.

ACKNOWLEDGMENTS

The authors are grateful to George Way, ADOT, for his guidance and advice throughout the implementation of AZNOS. The authors also thank Larry Scofield, of the Arizona Transportation Research Center, for his support and enthusiasm for this research. Thanks also go to the anonymous reviewers for their constructive comments.

REFERENCES

1. Kulkarni, R., K. Golabi, F. Finn, and E. Alviti. *Development of a Network Optimization System.* Woodward-Clyde Consultants, San Francisco, Calif., 1980.
2. Way, G. B. Network Optimization System for Arizona. *Proc., North American Pavement Management Conference,* Vol. 2, Toronto, Ontario, Canada, 1985, pp. 6.16–6.22.
3. Golabi, K., R. B. Kulkarni, and G. B. Way. A State Wide Pavement Management System. *INTERFACE Magazine,* Vol. 12, No. 6, 1982.

4. *An Advanced Course in Pavement Management Systems.* FHWA, U.S. Department of Transportation, 1991.
5. Thompson, P. D., L. A. Neumann, M. Miettinen, and A. Talvitie. A Micro-Computer Markov Dynamic Programming System for Pavement Management in Finland. *Proc., 2nd North American Conference on Managing Pavements,* Vol. 2, Toronto, Ontario, Canada, 1987, pp. 2.242–2.252.
6. Harper, W. V., and K. Majidzadeh. Use of Expert Opinion in Two Pavement Management Systems. In *Transportation Research Record 1311,* TRB, National Research Council, Washington, D.C., 1991, pp. 242–247.
7. Wang, K. C. P. *Pavement Network Optimization and Analysis.* Ph.D dissertation. Arizona State University, Tempe, 1992.
8. Wang, K. C. P., J. Zaniewski, G. Way, and J. P. Delton. Microcomputer Implementation of Pavement Network Optimization System. *ASCE Journal of Computing in Civil Engineering,* Vol. 7, No. 4, Oct. 1993, pp. 495–510.
9. Wang, K. C. P., J. Zaniewski, G. Way, and J. P. Delton. *Pavement Network Optimization and Implementation.* Special Report AZ-SP-9301. Arizona Department of Transportation, 1993.
10. Simon, H. *The New Management Science.* McGraw-Hill, New York, 1977.