Revisions to Arizona Department of Transportation Pavement Management System

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The important aspects of the original network optimization system (NOS) used in the Arizona Department of Transportation (ADOT) are reviewed. The NOS has been an important instrument for the Highway Preservation Program since the early 1980s. However, no major updates have been conducted to the original NOS since its initial implementation. It was determined that there is a need to reevaluate the system since there are more than 10 years of pavement performance data available now and technology advancements in microcomputers. Several improvements should be made to the NOS model structure and the original transition probability matrices (TPMs). The factor of crack change was found to be insignificant in predicting the acceleration of pavement deterioration. Therefore, it was removed from the system. The effective rehabilitation actions were determined to be 6 instead of the original 17. In addition, new prediction models were established for all the road categories 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 performance. Pavement probabilistic behavior curves have been established and analyzed on the basis of Chapman-Kolmogorov equations. The new NOS structure improves the effectiveness and efficiency of the optimization. The enhanced NOS is implemented on a high-end microcomputer in the 32-bit operating environment. ADOT uses the new NOS to conduct financial analysis for more than 7,000 mi of highways with annual rehabilitation funding approaching $100 million.

A network optimization system (NOS) has been implemented by the Arizona Department of Transportation (ADOT) for more than a decade. It represented a significant advancement in applying operations research techniques to a pavement management system (PMS). An estimated $40 million was saved for the state of Arizona from 1980 to 1985 by using the results from NOS runs for the Highway Preservation Program (*1*). The capability of NOS to reliably conduct financial planning has been the driving force for ADOT's continued reliance on the instrument. This paper reviews the important aspects of the original NOS system and recommends revisions to NOS where deemed necessary. New transition probability matrices (TPMs) were developed to improve the reliability of the system. Pavement probabilistic behavior curves have been established and analyzed on the basis of Chapman-Kolmogorov equations. Accessibility rules were established to improve the Markovian prediction.

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INTERPRETATION OF ADOT PAVEMENT MANAGEMENT SYSTEM

In 1979 ADOT selected WoodWard-Clyde (WCC) to develop a PMS for the state highway network for programming and budgeting of highway preservation needs (*2*). The optimization procedure is unique among the existing PMSs. The elements of the ADOT PMS are the pavement management data base, the NOS, and report writing capabilities.

ADOT Pavement Management Data Base

The pavement management data base contains a record for each milepost of two-lane roads in the state and a record for each milepost in each direction for divided highways. There are 7,498 records, or sections, in the system. The fields in the data base contain location descriptors, pavement condition variables and historical information on traffic and maintenance. The pavement condition data include fields on the roughness, cracking, patching, rutting, flushing, and skid resistance. Each record contains the complete condition history of the section dating to the time when the data were first collected. The roughness data are collected with a Maysmeter and date to 1972. The cracking data are estimates of the percentage of the surface cracked and date to 1979. The data of rutting, patching, and flushes date from 1986, 1979, and 1979, respectively. The maintenance information includes fields for the most recent type of maintenance or rehabilitation project on the section.

NOS

The major features of the input data for NOS are the road categories, current condition of the pavements, TPMs, rehabilitation costs, infeasible actions, and condition standards. The output of the mainframe-based NOS enabled ADOT management to address the following questions on the basis of multiperiod NOS runs:

• What proportion of the pavements in each road category are expected to be in various condition states at the beginning of each time period?
• What is the most cost-effective rehabilitation program for the pavement network for each time period?
• What are the expected annual costs of pavement rehabilitation and routine maintenance?

Road Categories

Road categories are defined by

• Functional class—Interstate and non-Interstate;
• Traffic level—low, medium, and high;
• Region within the state—mountain, transition, or desert.

This produces 18 road categories. However, the low traffic level does not exist for the Interstate highways, thus the NOS uses 15 road categories. Road categories are treated independently by the NOS optimization procedure.

Condition States

The condition of the pavement network is defined in terms of the percentage of network that is in each condition state, defined as the following:

Factor	*Levels*	*Unit*
Roughness	<94, 94–142, >142	Maysmeter output (in./mi)
Cracking	0–10, 11–30, >30	Percentage of area
Cracking change	0–5, 6–15, >16	Percentage in 1 year
Index to first crack	1, 2, 3, 4, 5	N/A

The index to first crack was conceptually an estimate of the time between the construction or rehabilitation of the pavement to occurrence of the first crack. However, this index is used to select a TPM on the basis of the most recent rehabilitation. There are five levels of the index to first crack that are based on the type of rehabilitation treatment.

Roughness, cracking, and crack change are based on the observed condition of the pavement. There are 27 combinations of these factors. However, the combination of low-level crack and high level of crack change in 1 year is not feasible, resulting in 24 feasible combinations. When the five levels of index to first crack are considered, there are 120 combinations, as presented in Table 1.

Each pavement section in the network is placed in a road category and a condition state to define the characteristics of the population for the optimization process. Once these characteristics have been defined, the NOS operates with the percentages, or fractions, of pavements rather than considering specific pavement sections in the data base. For example, the NOS can determine the percentage of pavements in specific condition states that should be overlaid but not the specific sections of highway that need the treatment. NOS is capable of assigning actions to each mile in the system; however, this feature is not often used for project selection because of the impractical assignment of different actions to each mile.

TABLE 1 Condition State Numbering System

			INDEX TO FIRST CRACK, I_c				
R_o	C_o	C_p	INDEX 1	INDEX 2	INDEX 3	INDEX 4	INDEX 5
1	1	1	1	25	49	73	97
1	1	2	2	26	50	74	98
1	2	1	3	27	51	75	99
1	2	2	4	28	52	76	100
1	2	3	5	29	53	77	101
1	3	1	6	30	54	78	102
1	3	2	7	31	55	79	103
1	3	3	8	32	56	80	104
2	1	1	9	33	57	81	105
2	1	2	10	34	58	82	106
2	2	1	11	35	59	83	107
2	2	2	12	36	60	84	108
2	2	3	13	37	61	85	109
2	3	1	14	38	62	86	110
2	3	2	15	39	63	87	111
2	3	3	16	40	64	88	112
3	1	1	17	41	65	89	113
3	1	2	18	42	66	90	114
3	2	1	19	43	67	91	115
3	2	2	20	44	68	92	116
3	2	3	21	45	69	93	117
3	3	1	22	46	70	94	118
3	3	2	23	47	71	95	119
3	3	3	24	48	72	96	120

R_o: Roughness Level
C_o: Crack Level
C_p: Crack Change

Rehabilitation Actions

The NOS considers 17 rehabilitation actions, as given in Table 2. The first action is routine maintenance; it is assumed that all pavements that are not selected for a different rehabilitation treatment will receive routine maintenance. The second alternative, seal coat, is a preventive maintenance treatment and will not substantially improve the condition of a deteriorated pavement. The third treatment, asphalt concrete friction course (ACFC) is usually applied to improve skid resistance or roughness, although there will be a reduction in cracking also. The remaining treatments provide structural improvement. There are some differences in the actions available for the Interstate and non-Interstate roads. The costs of each of the rehabilitation actions are given in dollars per square yard (Table 2). They are updated annually or as needed.

TPMs

The performance model used in the NOS is based on TPMs. A transition probability, $p_{ij}(a_k)$, is the proportion of roads in

TABLE 2 Rehabilitation Action Table

ACTION	COST ($/SY)		I_c INDEX	TO STATES
	INTERSTATE	NON-INTERSTATE		
1. ROUTINE	0	0	*	1 - 24
2. SEAL COAT	1.19	1.20	2	25 - 48
3. ACFC	1.33	1.34	2	25 - 48
4. ACFC+AR	4.55	4.58	3	49 - 72
5. ACSC	2.59	2.61	2	49 - 72
6. AC +AR	8.96	9.02	3	49 - 72
7. 2"AC+FC	6.51	6.56	4	73 - 96
8. 2"AC+AR+FC	8.68	8.74	4	73 - 96
9. 3"AC+FC	9.10	9.17	4	73 - 96
10. 3"AC+AR+FC	11.27	11.35	4	97 - 120
11. #, **	5.19	6.42	3	97 - 120
12. #, **	10.44	9.02	4	97 - 120
13. #, ***	10.96	6.49	4	97 - 120
14. #, ***	11.86	8.46	5	1 - 24
15. #, ***	13.83	10.43	5	1 - 24
16. 4"AC+FC	11.69	11.77	5	1 - 24
17. 5"AC+FC	14.28	14.38	5	1 - 24

*: I_c in this category depends on the most recent action
ACFC is Asphalt Concrete Friction Course
AR is Asphalt Rubber
ACSC is Asphalt Concrete Surface Course
AC is Asphalt Concrete
FC is Friction Course
is removal-replace plus 2" AC for interstate with increasing removal-replace thicknesses
** is 2"AC plus Seal Coat, and 3"AC plus Seal Coat for non-interstate respectively
*** is removal-replace plus FC for non-interstate with increasing remove-replace thicknesses
I_c is the index to first crack

state i that move to state j in 1 year if the kth rehabilitation action is applied. It defines the probability of transition from one condition state to another in 1 year under one of the rehabilitation actions, including routine maintenance. The current matrix structure of transition probabilities in NOS consists of 15 road categories, 17 actions (including routine maintenance, seal coat, and 15 rehabilitation actions), and 120 states. The total number of matrices is $15 \times 17 = 255$.

All pavement sections, within a road category, are placed in 1 of the 120 condition states. However, since the index to first crack is based on the most recent rehabilitation action, a given condition state can transition to only 1 of the 24 condition states associated with the index to first crack in 1 year under routine maintenance, as given in Table 1.

The concept of the transition between condition states is shown in Figure 1. After construction or reconstruction, a pavement remains in Condition State 1 to 24 until an action other than routine maintenance is applied. Once a nonroutine maintenance action is applied, a new index to first crack is defined and the condition state of the pavement is restricted to 1 of the 24 condition states associated with that index. This structure prohibits a pavement that has received a nonroutine maintenance action from entering Condition States 1 to 24.

In the year in which a nonroutine maintenance action is applied, a transition matrix is used to predict the proportion of pavements in each of the 24 condition states associated with the index. Generally one would expect that a very high percentage of the pavements would be transformed to the best-condition state. For example, in Table 2 the index to first crack is 5 for a 5-in. overlay with a friction course. Table 1 shows that the condition states for this index are 97 to 120, with 97 being the best condition state. The probability approaches 1.0 that this treatment would result in a pavement in Condition State 97. Seal coat and friction courses generally will hide cracks for 1 or 2 years, but seal coat will not improve roughness. These treatments have an index to first crack of 2. The most probable condition states following these treatments are 25, 33, and possibly 41.

In summary, for each of the 15 road categories there is one TPM that is 120×120, grouped in five blocks of 24×24, for the routine maintenance action. In addition, there are 16 TPMs for the nonroutine maintenance actions; these matrices are 120×24.

For the development of the NOS, regression equations were derived from a sample of pavement performance data (*3*). TPMs could then be calculated from the regression equations.

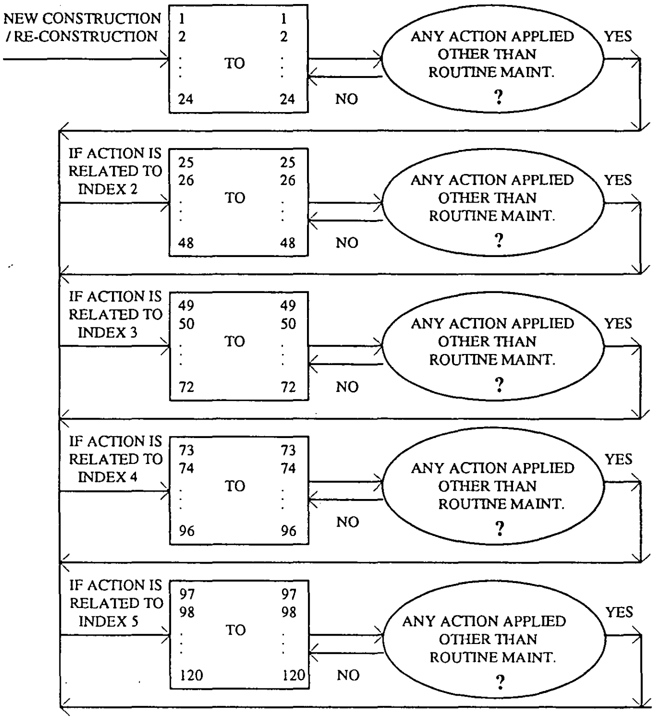

FIGURE 1 Flow chart of transition process of pavement condition states.

Regression equations were developed for changes in

- Roughness under routine maintenance,
- Amount of cracking of newly constructed roads under routine maintenance,
- Roughness following an overlay, and
- Cracking following an overlay.

The methodology of calculating transition probabilities for a given combination of traffic volumes and regional factors was detailed by Kulkarni et al. (*2*).

Infeasible Actions

Initial testing of the original NOS demonstrated that Rehabilitation Action 3, ACFC, was selected a disproportionate amount of the time. This was due to the inability of the TPMs to distinguish between the long-term performance of the ACFC and structural overlays. Therefore, the input to the program was modified to allow the user to prohibit the consideration of certain actions for certain condition states.

Condition Standards

Condition standards define acceptable levels of pavement condition to meet the needs of the traveling public; they are set by management policy. The user of the NOS inputs the minimum percentage of sections that should be in good condition and the maximum percentage that can be in poor condition for each of the traffic levels for Interstate and non-Interstate highways.

Optimization Algorithm

The NOS uses a linear optimization method coupled with the Markov chain concept for minimizing the overall costs of preserving the highway network to a set of specified standards over a planning period. The techniques of using linear programming and the Markov chain concept were initiated by Manne and by Wolfe and Dantzig in the early 1960s for large systems (*4,5*). They were subsequently adopted by WWC and ADOT to solve highway network investment problems (*2,6*). Hillier and Lieberman describe the basic model setup of this linear programming formulation (*7*). The transition process of pavement condition state conforms to the finite-state Markov chain process.

Two stages are needed to complete the optimization process. 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. The core of the optimization model lies in the following two transition equations for the two stages of optimization, respectively:

First stage: steady-state problem

$$\sum_k w_{i,k} = \sum_{i,k} w_{i,k} \cdot p_{ij}(a_k) \tag{1}$$

Second stage: multiperiod problem

$$\sum_k w^l_{j,k} = \sum_{i,k} w^{l-1}_{i,k} \cdot p_{ij}(a_k) \qquad \text{for } 1 < l \le T \tag{2}$$

RECOMMENDATIONS FOR IMPROVING SYSTEM

The development of the ADOT PMS was a significant advancement in using new technologies and was recognized nationally in 1982 (*6*). However, the current state of the art and data bases that have subsequently become available provide the means to revisit the original developments to determine whether revisions are warranted. Since the heart of the NOS analysis method is the TPMs, these are examined in this paper.

The regression equations were the basis for the generation of the TPMs. Because of inadequate data, sample data were used to build regression equations instead of using actual pavement performance data to generate transition probabilities. It was also assumed that the probabilistic behaviors of condition transition of pavements for both Interstate and non-Interstate highways were the same.

Four factors are used to determine pavement condition. Three of the four factors are related to pavement structural capabilities: percentage crack, crack change, and index to first crack. Only one factor, roughness level, is used as the measurement of ride quality. However, pavement rehabilitation strategies are dominated by ride quality rather than structural soundness (8). The review of the existing system also indicates that the NOS problem size is probably excessive. In addition, the existing levels for the boundaries defining condition states are not representative of the levels used by the engineering staff for determining rehabilitation needs or actions. Therefore, new levels of pavement classification are needed. In this paper, the TPMs were evaluated with respect to long-term behavior and new TPMs were developed on the basis of pavement management data base.

Under the original system, poor pavements can transition to good condition under routine maintenance. This unrealistic phenomenon is attributed to the assumption during the development of the original NOS that the transition probabilities conform to normal distribution. As shown in Figure 2, there is a probability, p_{ih}, under routine maintenance for a pavement, whose roughness value is within the medium roughness level, to transition to the low roughness level. Defining the transition probability for any pavement in the medium roughness level to transition to a low roughness level under routine maintenance requires integrating the specific probabilities, such as shown in Figure 2, within the limits that define the levels. This unrealistic behavior of transitioning to a lower roughness level under routine maintenance does not occur in the field during a long observation period, so accessibility rules were introduced to prohibit some of the transitions from occurring in the model.

Reducing Size of TPMs

When the structure of the condition states was set up in the early 1980s, there was little information on the crack change in the pavement management data base. During the development of the system it was assumed that crack change would play an important role in predicting pavement structural deterioration rate. However, examining the pavement performance data base shows that crack change of more than 5 percent is a rare event (Table 3). Only 4.2 percent of Interstate and 6.5 percent of non-Interstate sections had a crack change, from one year to the next, of more than 5 percent. In addition, the occurrences of crack changes over 15 percent occurred in less than 1 percent of the records.

Table 4 demonstrates that more than 5 percent crack change in one year does not indicate that there will be a high level of crack in the following year. This is in conflict with the concept that the rate of distress development increases as the pavement deteriorates. The failure of the data to demonstrate an increasing rate of deterioration could be attributed to the 5 percent level of crack change used in the analysis. However, the deviations of visual examination of percentage cracking can be as high as 5 percent at the same location either by different field crews or at different times within 1 year. This deviation can be even higher when the pavement is highly cracked. For example, when a pavement is 20 percent cracked, it is very possible that the visualized percentage crack range is between 15 and 25 percent. Therefore, the analysis based on the 5 percent level of crack is reasonable.

Further evidence is illustrated in Figure 3. The data of percentage crack for the Interstates were averaged on a yearly basis for 15 years. They show that there was an average of 4½ years between the rehabilitation and the occurrence of

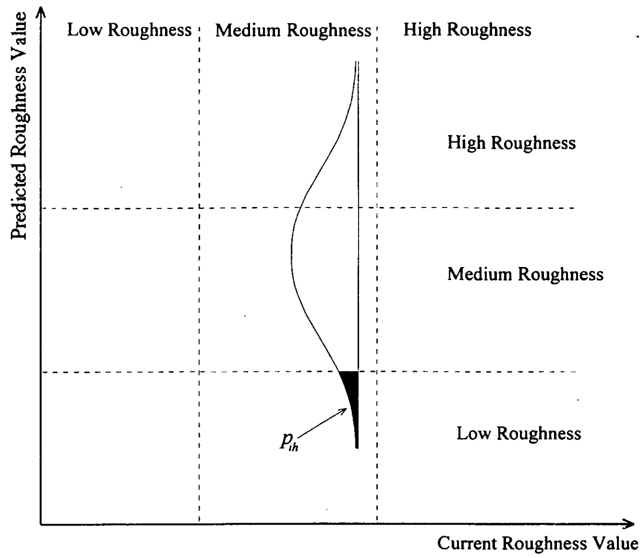

FIGURE 2 Concept of using normal distribution to define TPM for factor of roughness in original NOS.

TABLE 3 Percentage of Records in First Crack

Crack Change (%)	% of Total Record-Year (Interstate)	% of Total Record-Year (Non-Interstate)
0 to 5	95.90	93.50
6 to 15	3.80	5.90
Over 15	0.30	0.6 0

TABLE 4 Percentage of Records in Consecutive Multiyear Crack Change Over 5 Percent

Multi-Year Crack Change Over 5%	% of Total Record-Year (Interstate)	% of Total Record-Year (Non-Interstate)
Consecutively Two-Year	0.40	0.57
Consecutively Three-Year	0.03	0.06
Consecutively Four-Year	0.00	0.00

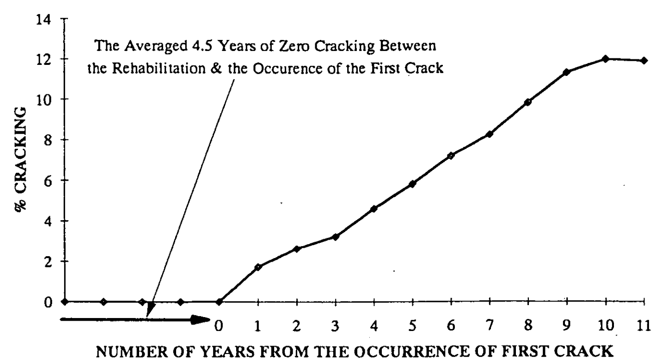

FIGURE 3 Average percentage cracking over time after rehabilitation for Interstate highways.

the first crack for the Interstate network. When the percentage crack increased over the next 11 years, as shown in Figure 3, the relationship of crack change over time is approximately linear. The rapid pavement structural deterioration after the development of first crack was not observed in this figure.

Therefore, from this analysis, it is evident that crack change, as defined in the existing system, is not an important indicator of the acceleration of pavement deterioration. The new structure of condition states without considering crack change is given in Table 5.

Reducing Number of Rehabilitation Actions

There are 17 rehabilitation actions in the original NOS. The initial concept of using this number of actions was to provide guidance for the pavement design process to select the "best" overlay design strategy. On the basis of the effectiveness of the action in the year of application, there are three categories of action: routine maintenance, light treatments, and heavy treatments. Light treatments have an index to first crack of 2 but the initial effect of the treatments in this category varies depending on the type of action—that is, a seal coat does not improve roughness but ACFCs and asphalt concrete surface courses improve roughness. Heavy treatments, with index to first crack of 3 to 5, have a high probability, approaching 1.0, of improving the pavement to the best condition state. In the NOS all actions with a particular index to first crack use the same transition probabilities under routine maintenance. Therefore, the NOS only models the behavior of five action groups under routine maintenance, one for each index to first crack. This restricts the NOS to selecting the least-cost actions for the heavy treatment categories. The difference in the initial condition within the light treatment category enables the NOS to distinguish between the effectiveness of the seal coats and the other light treatments. Therefore, the NOS can optimize only on 6 actions, not 17. Experience with running the NOS supports this conclusion. The infeasible actions input to the NOS were used to restrict the system's use of actions that were deemed inappropriate for certain condition states. Therefore, since the model can select between only six actions, the structure of the model can be simplified by eliminating 11 actions without compromising the effectiveness of the model. The new rehabilitation actions are presented in Table 6. Note that the new actions list does not distinguish between Interstate and non-Interstate.

Roughness and Cracking Level Boundaries

The existing roughness and cracking classification levels for NOS were based on the information available in the early 1980s. However, the pavement performance data show that these levels are no longer appropriate. For example, Crack Level 2 represents 11 to 30 percent crack in the pavement and is currently used in the NOS as the medium crack level. However, pavements at a crack level of more than 10 percent are not in an acceptable condition state. In addition, a Maysmeter value of 90 is too rough to be considered in the good category, as is the case with the existing NOS system. And the existing classification puts a pavement at 10 percent crack and Maysmeter number of 80 into the best condition state, which no longer can be viewed as a good pavement by today's engineering practice.

Therefore, two sets of pavement condition state criteria are needed for Interstates and non-Interstates respectively. The definition of the new classifications should be based on the current pavement condition. In addition, on the basis of the ADOT pavement design practice, pavements with serviceability indexes (SIs) of less than 3.0 for Interstates and 2.5 for non-Interstates are considered to be in the poor condition. Therefore, pavements with SIs of less than 3.0 and 2.5 were classified to be in the high roughness category for Interstates and non-Interstates, respectively. It is generally assumed that an Interstate pavement with an SI higher than 3.5 is in good condition. Therefore, Interstate pavements with SIs higher than 3.5 were classified to be in the low roughness level. For the same reason, non-Interstate pavements with SIs higher than 3.0 were classified to be in the low roughness level. Equation 3 shows the correlation between the SI and Maysmeter numbers:

$$SI = 0.3488 + 4.6836 \cdot 0.9970^{(R-4.255)/0.54} \quad (3)$$

where R is the calibrated Maysmeter value.

Ride quality consistently dominates the highway preservation program, so the importance of determining cracking levels for Interstates and non-Interstates is secondary. There-

TABLE 5 New Condition State Numbering System

R_o	C_o	INDEX TO FIRST CRACK, I_c				
		1	2	3	4	5
1	1	1	10	19	28	37
1	2	2	11	20	29	38
1	3	3	12	21	30	39
2	1	4	13	22	31	140
2	2	5	14	23	32	41
2	3	6	15	24	33	42
3	1	7	16	25	34	43
3	2	8	17	26	35	44
3	3	9	18	27	36	45

TABLE 6 New Action Groups of Rehabilitation Actions

ACTION GROUP	ACTIONS	AVE. COST($/SY) INTERSTATE	AVE. COST($/SY) NON-INTERSTATE
1	ROUTINE MAIN.	.05	.05
2	SEAL COAT, ACFC, ACSC	1.20 - 2.6	1.25 - 2.7
3	ACFC+AR,ARAC	5.00 - 8.90	5.10 - 9.00
4	2"AC+AR,3"AC+FC	9.20 - 11.00	9.30 - 11.20
5	4.5"AC+FC & OTHER HEAVIER ACTIONS	12.00 +	12.00 +

The rehabilitation costs were derived based on 1990 data.

fore, the classification of cracking levels is grouped into the same ranges for both Interstates and non-Interstates. From the information given, it is determined that the following new classification levels are appropriate:

Function	*Factor*	*Levels*	*Unit*
Interstate	Roughness	<76, 76–104, >104	Maysmeter output (in./mi)
	Cracking	0–8, 6–15, >15	Percentage of area
Non-Interstate	Roughness	<94, 94–142, >142	Maysmeter output (in./mi)
	Cracking	0–8, 9–15, >15	Percentage of area

Development of New TPMs

Ideally, the transition probabilities are obtained by observing the performance of a large number of pavements under different rehabilitation actions over a long period. More than 10 years of pavement performance data are available now. Therefore, the proportion of roads moving from states i to j in 1 year, following kth rehabilitation action, can be determined directly from the performance data base. The following equation is applied to calculate the transition probability from state i to state j for each road category on the basis of the new pavement condition state structure:

$$p_{ij}(a_k) = \frac{m_j(a_k)}{m_i(a_k)} \quad \text{for } i,j = 1, \ldots, 45,\ k = 1, \ldots, 6 \qquad (4)$$

where

$p_{ij}(a_k)$ = transition probability from states i to j after action k is taken;
$m_j(a_k)$ = total number of miles where condition states before and after action k are i and j, respectively; and
$m_i(a_k)$ = total number of miles where condition state before action k is i.

In addition, the following probability property must be observed by adjusting the biggest value among $p_{ij}(a_k)$, for j = 1, . . . , 45, and for each i and k:

$$\sum_{j=1}^{120} p_{ij}(a_k) = 1 \quad \text{for } i = 1, \ldots, 45,\ k = 1, \ldots, 6 \qquad (5)$$

The matrices have been generated for both Interstate and non-Interstate highways on the basis of the pavement performance data from 1979 to 1991. Transition probabilities predict pavement condition states on the basis of a finite-state Markov Chain process (*2,6*). Thus, the TPMs consist of one-step probabilities and can only be directly used to predict the change in condition state from one year to the next.

The Chapman-Kolmogorov equation (*7*) provides a method for computing the n-step TPM from a single-step TPM. The matrix for n-step transition probabilities can be obtained by multiplying matrices of one-step transition probabilities:

$$P^{(n)} = P \cdot P \cdots P = P^n \qquad (6)$$

Therefore, the transition probabilities of pavement condition for n years can be obtained from the existing one-step transition probabilities. As a result, long-term pavement probabilistic behavior can be revealed. Figure 4 shows typical pavement probabilistic behavior curves. The upper curve shows the probability of pavements' starting in the best condition state and remaining in the best condition state over time. The lower curve shows the probability of pavements' starting in the best condition state and transitioning to the worst condition state over time.

One set of TPMs was generated from the pavement performance data base based on the new roughness and cracking levels. The new transition probabilities for remaining in the best condition under routine maintenance are shown in Table 7 for the 15 road categories. The table also presents the number of observations used to determine the probabilities. The probabilities with small sample sizes in the tables should not be used. It should be noted that the probabilities based on the new levels are smaller than those based on the original levels. This indicates that if the current pavement perfor-

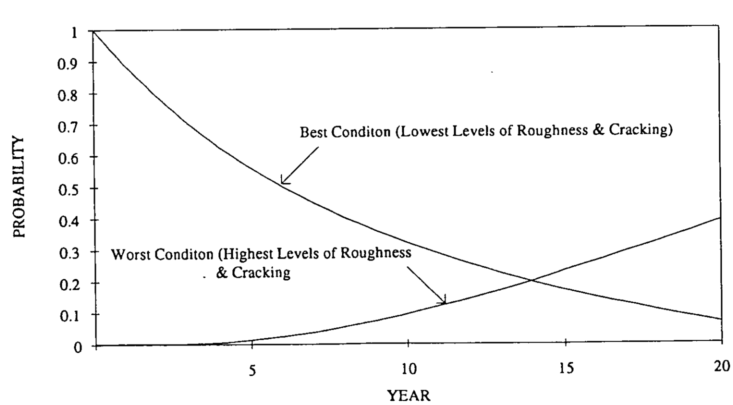

FIGURE 4 Pavement probabilistic behavior starting from best condition state under routine maintenance.

TABLE 7 Transition Probability Comparison Based on New Classification of Roughness and Cracking Levels

TRAFFIC LEVEL		LOW			MEDIUM			HIGH		
REGION		DESERT	MEDIUM	HIGH	DESERT	MEDIUM	HIGH	DESERT	MEDIUM	HIGH
REHABILITATION ACTIONS / ROAD CATEGORY: INTERSTATE	1	N/A	N/A	N/A	0.91/1300	0.909/263	N/A	0.837/1890	0.855/1475	0.833/42
	2	N/A	N/A	N/A	0.919/478	0.905/21	N/A	0.82/423	0.889/458	0.763/118
	3	N/A	N/A	N/A	1.0/16	N/A	N/A	0.692/13	N/A	0.5/2
	4	N/A	N/A	N/A	0.862/435	1/7	N/A	0.847/785	0.83/783	0.939/98
	5	N/A	N/A	N/A	0.902/325	1/3	N/A	0.823/1172	0.893/693	0.928/499
NON-INTERSTATE	1	0.333/24	0.771/201	0.75/32	0.857/356	0.836/317	0.718/209	0.703/121	0.869/206	0.773/88
	2	0.836/311	0.794/656	0.806/366	0.79/854	0.838/1022	0.793/834	0.741/197	0.7/50	0.707/92
	3	N/A	0.962/26	N/A	0.958/118	0.88/25	0.766/47	0.881/59	N/A	N/A
	4	0.581/31	0.704/287	0.514/35	0.869/465	0.809/236	0.923/39	0.923/13	0.7/20	0.143/7
	5	N/A	N/A	N/A	0.833/102	N/A	1.0/9	N/A	N/A	N/A

NOTE:
The first number in the cell is the probability to stay in the best condition under routine maintenance for each rehabilitation action,
The second number in the cell indicates the sample size used to compute the probability,
N/A = Sample data are not available.

mance standards are used, the pavement preservation needs will be increased because of the more stringent roughness and cracking classifications.

In some instances the transitions do not exist in the pavement performance data files or the probability based on this transition is not representative of the real-world situation because of the small sample size. Therefore, to fulfill model requirements, the regression-based transition probabilities from the original NOS, or manually generated probabilities based on engineering judgment, can be used in the recommended model. This will not affect the output of the model substantially because these transitions are rarely if ever used in the optimization process.

Accessibility Rules

Condition state j is termed to be accessible from state i if $p_{ij}(a_k) > 0$ (*7*). No accessibility rules for routine maintenance were established in setting up the original TPMs. As a result, an illogic situation can occur when performance predictions are made by using a TPM for a pavement section in poor condition, such as State 24, high roughness and cracking. For example, Figure 5 shows that 10 percent of pavements in the worst condition will transition to the best condition state over 20 years under routine maintenance. However, in reality pavements in poor condition will not significantly improve over time under routine maintenance.

It is recommended that the data showing pavement performance improvement under routine maintenance be discarded and accessible condition states for routine maintenance be established for the development of new matrices. The pavement performance data base demonstrates that the pavement condition will not deteriorate two levels in 1 year. Accessibility rules, which prevent an improvement in pavement condition and deterioration of two levels in 1 year, were implemented by setting the probability of an illogical transition to 0. Table 8 gives the accessible transitions based on the rules, from Condition States 1 to 9. The same rules apply to Condition States 10 to 45 on the basis of roughness and cracking levels.

Figure 6 shows the effect of the accessibility rules for Interstates with medium traffic in the desert region. The accessibility rules result in a more rapid reduction in the percentage of pavements in the best condition state, and pavements

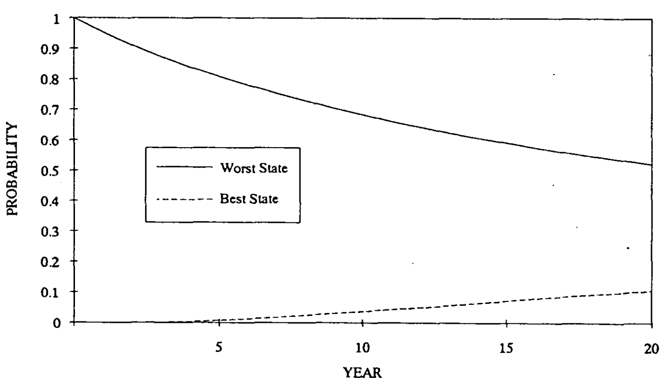

FIGURE 5 Pavement probabilistic behavior starting from worst condition state under routine maintenance on basis of original TPMs.

TABLE 8 Accessibility Table for Condition States 1 to 9 Under Routine Maintenance

FROM	TO
1	1, 2; 4, 5
2	2, 3; 5, 6
3	3; 6
4	4, 5; 7, 8
5	5, 6; 8, 9
6	6, 9
7	7, 8
8	8, 9
9	9

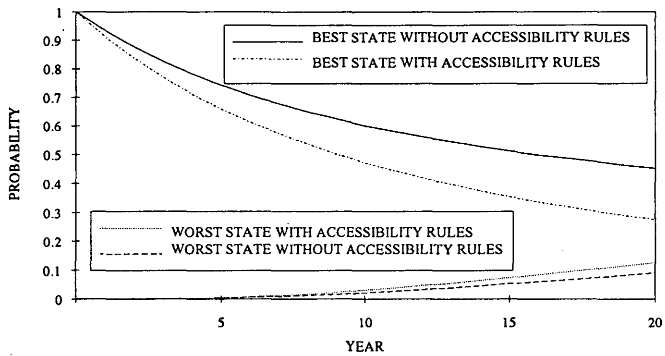

FIGURE 6 Pavement probabilistic behavior starting from best condition state under routine maintenance, with and without accessibility rules.

have a higher probability of transitioning to the worst condition state over time. It is clear that the probabilistic behavior curves presented in Figure 6 are more realistic than those in Figure 4.

CONCLUSION

The concept of the Markov chain has been used to predict pavement performance for more than a decade. The time-independent property of the Markov process is suitable for the transition equations shown by Equations 2 and 3 in the NOS linear formulation. A new study conducted by ADOT determined that the fit of Markovian predictions with actual pavement behavior was satisfactory (*9*).

A new structure of pavement condition states was set up in this paper for the optimization model used by ADOT. New TPMs were established for both the Interstates and non-Interstates on the basis of the 13-year pavement performance data base. The TPMs were modified with accessibility rules to improve the prediction of pavement performance. New analysis tools were revealed to analyze the long-term probabilistic behavior of the pavement. The revised model has been successfully implemented to an advanced 32-bit operating system environment in a high-end 486 microcomputer (*9*). ADOT is using the new NOS to generate the next 5-year Highway Preservation Program with an annual expenditure approaching $100 million. It is believed that these enhancements to the PMS will improve the reliability and accessibility of the system for ADOT.

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