OPTIMIZATION OF INFRASTRUCTURE SYSTEMS MAINTENANCE AND IMPROVEMENT POLICIES

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ABSTRACT: This paper presents an approach for the joint optimization of maintenance and improvements of the components of a network of infrastructure facilities. In the literature, these two problems have often been handled separately, probably because the problems seem quite different. However, these decisions (maintenance and improvement) are not independent due to the presence of trade-offs between the two sets of policies. We develop a Markov decision model for the joint optimization of maintenance and improvement, thus improving the budget allocation among facilities in the network between the two sets of activities and within each set. The model is used to solve for steady-state policies, but relaxes the assumption of age-homogeneous condition-state transition probabilities, which has been criticized in the literature. Moreover, the model allows for the possibility of not exhausting the annual budget available every year, so that part of it can be spent more efficiently in later years. The paper includes a case study that demonstrates that substantial savings can be achieved through the joint optimization of maintenance and improvement policies.

INTRODUCTION

This paper presents an approach for the joint optimization of maintenance and improvements of the components of a network of infrastructure facilities such as highway pavements or bridges. In state-of-the-art infrastructure management systems, such as Pontis (FHWA 1993) and BRIDGIT (NET 1994), these two problems have usually been handled separately. This is partly because the budgets allocated for maintenance and for improvements often come from separate sources, and also because the problems seem quite different. However, the two sets of decisions (maintenance and improvement) are not independent. For example, rather than maintaining a bridge for 20 years before finally replacing it, instead savings can often be achieved by replacing it now or in the near future.

It is important at the outset to delineate clearly the difference between maintenance and improvement actions. Maintenance includes actions that retard or correct the deterioration of infrastructure facilities. For example, for highway pavements these actions include crack sealing as well as resurfacing; for bridges, they include deck patching. By improvement, we mean the set of actions that alter the functionality of the facility while returning its condition to its best possible condition state. For pavements, this includes reconstruction, whereas for bridges an example is deck replacement.

The objective of this paper is to present a model for the joint optimization of maintenance and improvement, with the goal of improving the budget allocation among facilities in a network between the two sets of activities and within each set. The paper includes a realistic case study that demonstrates that substantial savings can be achieved through the joint optimization of the two sets of decisions.

One of the fundamental differences between the way in which maintenance and improvement policies have been addressed in the literature is in the treatment of the time dimension. In previous research, the maintenance problem has been recognized to depend on time. An important aspect of the maintenance problem is the trade-off between inexpensive but frequent routine maintenance, and expensive but sporadic rehabilitation actions, subject to a minimum condition level and budget constraints.

Many state-of-the-art infrastructure management systems utilize Markov decision processes for maintenance and rehabilitation decision making (Golabi et al. 1982; Carnahan et al. 1987; Carnahan 1988; Feighan et al. 1988; Harper et al. 1990; Gopal and Majidzadeh 1991; Madanat and Ben-Akiva 1994). In this methodology, facility condition is represented by a discrete state, and the deterioration process is modeled as a discrete Markov chain.

The underlying assumption of Markov processes is that at any time t, the distribution of condition states at time $t + 1$ depends on the history of the facility only through the present state. Another common assumption is that the transition probabilities do not depend on age, i.e., that the transition probabilities are age-homogeneous. While the second assumption is not necessary to optimize transient maintenance policies in finite horizon problems, it has been imposed to permit the solution for steady-state maintenance policies in infinite horizon problems (Golabi et al. 1982). Unfortunately, this assumption is supported neither by mechanistic knowledge of material behavior nor by empirical observations of facility deterioration. Indeed, a large body of empirical work has shown that age (i.e., time since construction or reconstruction) is a significant determinant of facility's deterioration rate (Jiang et al. 1989; Madanat et al. 1995, 1997). In this paper, we shall relax this assumption, as it is not necessary to obtain steady-state maintenance and improvement policies.

At the network level, the Markovian transition probabilities should be interpreted as the expected fraction of facilities in a certain state that will deteriorate to another state in one time period given a selected maintenance activity, rather than the probability of one section deteriorating from one state to another. This expectation is taken over the distribution of ages of the facilities in that state. Therefore, even though age affects the transition probabilities of each facility, the average fraction is independent of age if the distribution of ages in each state remains more or less the same. Thus, the assumption of age-homogeneous transition probabilities is less controversial at the network level.

Network level formulations of the maintenance optimization problem have typically used a randomized-policy approach to the Markov decision process (Golabi et al. 1982; Harper et al. 1990; Gopal and Majidzadeh 1991). The maintenance optimization problem has been solved for two separate but related cases: The finite horizon and the infinite horizon cases. On the

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other hand, the improvement problem has usually not accounted for the time dimension.

Improvement Problem

As mentioned in the Introduction, the improvement issue is often formulated in the literature as a time-static problem. By time-static optimization, we mean that the model used does not consider the optimal scheduling of improvement activities over time. The decision is either to perform an improvement this year, or do nothing and decide next year. This myopic approach does not consider the possibility that an improvement activity performed this year might have produced higher user benefits had it been delayed by a few years.

In the improvement problem, we start with a set of possible improvements, a set of facilities, and a set of rules that specify whether an improvement can be applied to a facility. The objective is to maximize user benefits resulting from actions taken on facilities subject to budget constraints and facility interconnection constraints. This is a typical integer optimization problem.

Infinite Horizon Maintenance Problem

The infinite horizon model assumes a steady-state distribution of facilities among the condition states, and a steady-state distribution of maintenance activities among these states. This means, for a given state, that the same overall fraction of facilities will be found in each state in every time period. It also means that the budget required to maintain the network in this distribution is the same in each time period, because the distribution of activities is also constant.

This assumption is defensible, because it is expected that highway agencies seek a situation in which both network quality and budget requirements are stable. The infinite horizon model is used to seek such steady-state distributions, and if they exist, to find the one that minimizes the expected social costs (agency plus user costs) subject to quality and budget constraints.

The following notation will be used:

- P_{aij} = transition probability from state i to state j given activity a:
- W_{ai} = fraction of the network facilities that are in state i and have action a applied to them; the W_{ai} must satisfy the following:

$$\sum_a \sum_i W_{ai} = 1$$

$$\sum_a \sum_i W_{ai} P_{aij} = \sum_a W_{aj}, \ \forall j$$

This second constraint is a consequence of the steady-state assumption. Indeed, $\Sigma_i W_{ai} P_{aij}$ is the fraction of the network to which action a was applied in the previous time period and that is now in state j. Therefore, $\Sigma_a \Sigma_i W_{ai} P_{aij}$ is the fraction of the network that is in state j now. By definition of the steady state, this is $\Sigma_a W_{aj}$

- U_{ai} is the user costs for facilities in state i to which activity a is applied.
- C_{ai} is the agency costs for facilities in state i to which activity a is applied.
- λ = degree of user cost contribution to the objective function.

The cost minimization problem is

$$\text{Min} \sum_a \sum_i W_{ai} * (C_{ai} + \lambda U_{ai})$$

subject to

$$(1) \sum_a \sum_i W_{ai} = 1$$

$$(2) \sum_a \sum_i W_{ai} P_{aij} = \sum_a W_{aj}, \ \forall j$$

$$(3) \ \text{BMIN} < \sum_a \sum_i W_{ai} C_{ai} < \text{BMAX}$$

$$(4) \ \text{CMIN}_l < \sum_{i \in l} \sum_a W_{ai} < \text{CMAX}_l, \ \forall l$$

The objective function in this program consists of the total social costs, including user and agency costs. The decision variables are the W_{ai}. Constraints (1) and (2) were described earlier. Constraint (3) is a budget constraint: The total agency costs must lie between a minimum and a maximum budget. Constraint (4) is a quality constraint, which specifies that the fraction of the network in Class l (a subset of the possible condition states) must fall between a maximum and a minimum limit. For example, if l represents the set of condition states considered ''poor,'' Constraint (4) will limit the fraction of the network in Class l to be no more than a certain maximum.

We note that the steady-state solution, if it exists, does not depend on the initial state distribution of the network. The long-term Markov model can be run separately for different regions with different weather or traffic conditions (having different transition matrices), for a range of budget constraint combinations. Then an economically efficient budget allocation among regions can be performed, by finding a solution where it is not possible to save additional user costs by shifting money from any region to another. This is true when the partial derivatives of the user costs with respect to the agency costs are equal across regions.

We also note that the problem is a linear optimization problem, for which efficient solution algorithms exist. However, because the steady state represents an optimal distribution that the agency seeks to reach through its maintenance actions, it is not obvious that for any given initial conditions, this steady state can be achieved within a specified horizon. This depends on the transition matrices, the costs, and the constraints.

Finite Horizon Maintenance Problem

The objective of the finite horizon model is to take the network from its current distribution of condition states to the distribution of condition states prescribed by the infinite horizon model. Different approaches have been tried in the literature (Golabi et al. 1982):

1. Model each year separately, and for each year, minimize some value representing an ''average cost'' of being at some distance from the steady-state distribution. This approach is not very appealing theoretically because it is well known that a series of myopic optimizations can lead to a solution that is far from the global optimum.
2. Use a model which, with a minimum budget, tries to lead the network condition-state distribution to the steady-state distribution after a given period T. As mentioned before, this problem may not have a feasible solution; some specified tolerances can be introduced to achieve feasibility. This approach is more theoretically appealing, but more computationally intensive because it solves the transient policies problem in a single mathematical program.

In the second approach the objective is to minimize the total cost for the T time periods subject to conservation of state constraints (the Chapman-Kolmogorov equations), quality constraints (performance standards), and budget constraints.

MODEL FORMULATION

To develop a model that will integrate the two decision-making problems, the improvement policies must become time-dynamic. The challenge in combining the two problems is that the time scale for improvement (20 years or more) and the time scale for maintenance (1 year) are very different. This difference makes it difficult to solve for steady-state policies, because, if one does not manage a very large network, it may be very difficult to find a facility on which an improvement may be performed every year.

The solution is to consider a different time scale for the steady-state formulation. The steady-state policy should be defined on a T-year-cycle, which means that the distribution of facilities' states and actions in year $k + T$ is the same as in year k.

To represent both sets of decisions within the same model, we need to modify our notation as follows:

- t: Index for time.
- n: Index for a facility.
- b: Index for an action in the set of improvement actions.
- a: Index for an action in the set of maintenance actions.
- i, j: Indices of states in the set of the possible states of the facilities.
- $w^n_{ai}(t)$: Fraction of facility n in state i on which maintenance action a is performed at time t.
- $1^n_b(t) = 1$ if improvement action b is performed on facility n at time t, 0 otherwise

We assume that the following data are known:

- $C^b_{ai}(n, t)$: Agency cost to perform actions a and b on a unit of facility n in state i at time t.
- $U^b_{ai}(n, t)$: User costs if one unit of facility n is in the state i at time t when the policy (a, b) is performed.
- $B(t)$: Budget for year t in today's dollars.
- $P^b_{aij}(\text{age}(n, t))$: Probability for one unit of a facility to move from condition state i to state j between t and $t + 1$ when actions b and a are performed at time t; this probability depends on age.

The problem is now to minimize the costs to users and agency subject to Budget Constraints (3), Quality Constraints (4), Interconnection Constraints (6), and Model Structure Constraints (1), (2), and (5):

$$\text{MIN}\left[\sum_{t,n,b,a,i} w^n_{ai}(t) \times 1^n_b(t) \times [C^b_{ai}(n, t) + \lambda \times U^b_{ai}(n, t)]\right]$$

subject to

$$(1)\ \sum_{a,i} w^n_{ai}(t) = 1, \quad \forall n, t$$

$$(2)\ \sum_{b} 1^n_b(t) = 1, \quad \forall n, t$$

$$(3)\ \sum_{t=1}^{\tau}\sum_{n,b,a,i} w^n_{ai}(t) \times 1^n_b(t) \times C^b_{ai}(n, t) < \sum_{t=1}^{\tau} B(t), \quad \forall \tau$$

$$(4)\ C_{\min}(l, n, t) < \sum_{i \in l}\sum_{a} w^n_{ai}(t) < C_{\max}(l, n, t), \quad \forall l, n, t$$

$$(5)\ \sum_{b}\sum_{a} w^n_{aj}(t+1) \times 1^n_b(t+1) = \sum_{i}\sum_{b}\sum_{a} w^n_{aj}(t) \times 1^n_b(t) \times P^b_{aij}(\text{Age}(n, t)), \quad \forall t$$

$$(6)\ 1^n_b(t) = 1^{n'}_b(t), \quad \forall t, b, \quad \forall (n, n') \text{ connected for } b$$

Constraint (2) expresses the fact that the actions in the improvement set are mutually exclusive. This is achieved by including in the set all possible combinations of the actions. For instance, if the possible actions are vertical clearance improvement and widening, the set will include three actions: (1) Vertical clearance; (2) widening; (3) vertical clearance and widening.

Constraint (3) states that the agency is allowed to spend one part of its budget in a year to later use the other part more efficiently. This is achieved by constraining the sum of funds used up to any time τ to be less or equal to the sum of budgets for years 0 to τ.

Constraint (4) is a quality constraint where condition-states are combined in different classes l, and where the fraction of a facility in a class has a lower and an upper bound.

Constraint (5) expresses the fact that the fraction of the network in any state at a given time depends on the state distribution and the actions taken at the previous time through the transition probabilities.

Constraint (6) states that the same improvement policy must be applied to those facilities that are connected (for example, bridges that must carry the same capacity).

To study steady-state policies, we define a cycle length T, which introduces two more constraints, expressing the fact that after one cycle, the network state and activity distribution returns to the initial state distribution:

$$(7)\ w^n_{ai}(T) = w^n_{ai}(0), \quad \forall a, j, n$$

$$(8)\ 1^n_b(T) = 1^n_b(0), \quad \forall b, n$$

In fact, the cycle length T is a decision variable that will be optimized as well. The approach followed in this paper will be to solve the joint maintenance and improvement optimization problem for a range of values of T, and then select the value of T that yields the lowest value of the objective function.

The differences between this model and the maintenance-only optimization model described earlier are as follows:

- Improvement and maintenance policies are jointly optimized.
- The improvement policy is optimized over time.
- The agency does not have to spend all its annual budget every year; it can keep part of it in reserve to use it more efficiently later.
- The transition matrix depends on age.

Computational Issues

The network-level joint maintenance and improvement optimization problem formulated above is significantly larger, in computational terms, than either the infinite planning horizon or the finite planning horizon network-level maintenance optimization problem described earlier, because both the number of decision variables and the number of constraints are larger. If we have A different maintenance activities, B different improvement activities, N facilities, I states, L classes, and T years in each cycle, then the number of decision variables is: $NAIT + NBT$. The maximum number of constraints is $N*T$ (for Constraints 1) + $N*T$ (for Constraints 2) + T (for Con-

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straints 3) + $L*N*T$ (for Constraints 4) + T (for Constraints 5) + $T*B*(N - 1)*(N - 2)/2$ (for Constraints 6, assuming that each facility is linked to all other facilities in the network) + AIN (for Constraints 7) + BN (for Constraints 8), yielding approximately $BN^2T/2 + (2 + L)NT + (AI + B)N + 2T$ constraints. The minimum number of constraints is $(2 + L)NT + (AI + B)N + 2T$, which is the case if every facility is independent of all other facilities.

For comparison, the infinite planning horizon problem has only AI decision variables and $2 + I + L$ constraints. For the second formulation of the finite planning horizon problem, there are only AIS decision variables and $2S + IS + LS$ constraints, where S is the number of years in the finite horizon. Clearly, the reason for the vast difference in computational complexity between the joint problem and the simple maintenance problem is due to the fact that each facility must be represented individually in the joint problem (thus the dependence on N). This facility-specific representation is necessitated by the fact that improvements are selected for individual facilities, whereas maintenance can be optimized at the level of the network.

The solution of the joint problem is computationally feasible given the power of the computing platforms that are in use in many state highway departments. In any case, because this is a planning problem that is solved once every year, computational complexity is not a critical question. Further, as we show in this paper, it is possible to simplify the problem substantially by formulating it as cost-minimization problem applied at the facility level. Such a formulation reduces the number of decision variables to $AIT + BT$ and the number of constraints to a number between $(2 + L)T + AI + B + 2T$ and $BT/2 + (2 + L)T + AI + B + 2T$, which is a substantial improvement. This is the formulation that we used in the case study reported in the following section.

CASE STUDY

A case study of a network of bridge decks was used to demonstrate the application of the above formulation. The objective of the case study was to quantify the expected cost savings that can be achieved by integrating maintenance and reconstruction decision making within the same optimization problem. This was achieved by comparing the minimum budget required by the joint replacement and maintenance optimization to that required by running the maintenance and improvement models separately.

Data

The data used for the analysis were obtained from the literature (Cady 1981; Jiang et al. 1989); these consisted of bridge deck maintenance and reconstruction costs and transition matrices (Appendix I). There are two alternatives for maintenance (do-nothing and rehabilitation), and two alternatives for improvements (do-nothing and reconstruction).

In real problems, the maintenance and improvement choice sets may include more alternatives, but their total number would be of the same order of magnitude. Due to the difficulty in obtaining accurate data for all types of maintenance activities, it was necessary to limit the case to two types. However, this does not reduce the realism of the case study.

The condition-state of a bridge deck is described in this study by the Concrete Bridge Deck Condition Ratings (FHWA 1979), which classifies deck condition into 10 possible states (9 for the best state, 0 for the worst). User costs are not used; instead, it was assumed that the three worst states of the bridge were not acceptable and that users were indifferent among the other states. In fact, it is not very realistic to think that users' costs can be accurately quantified for every state of the facility. It is more realistic to set unacceptable states for the users, and to assign a very large penalty if the facility condition drops to one of these states.

Because the user costs have been replaced by constraints (States 0, 1, and 2 are not acceptable), the objective function becomes the agency budget necessary to maintain the network for a steady-state cycle. The model will minimize the budget required for a T-year cycle, given quality constraints and transition constraints. Therefore, we will not set any budget constraint, so that the solution of the cost-minimization problem will give the best utilization of a T-year period budget. We will then compare this optimal utilization of funds with the one achieved by the simple maintenance optimization problem, where the amount of money spent for network maintenance is constant every year.

Given that the transition matrices used in our model are the same for every bridge deck, the optimal policy for the network is the same as the optimal policy for a single bridge deck. This is equivalent to assuming that there are no economies of scale for the maintenance of a network composed of identical units.

Transition Matrices Depending on Time

We assume that the transition matrices for any given maintenance policy applied on the deck depend on the number of years since the last reconstruction, i.e., the age of the unit. We also assume that the greater the age of the bridge deck, the greater the probability of seeing a transition to the poorer states. It should be noted here that the transition matrix when a reconstruction is done does not depend on time.

We then obtain the rehabilitation matrices from the do-nothing transition matrices given in the literature (Jiang et al. 1989). The do-nothing transition matrices have a maximum of two nonzero elements in every row; we will maintain this structure. We assume that rehabilitation increases the state of the rehabilitated part of the bridge by one. Therefore, for a given age of the bridge, the rehabilitation transition matrix at age t will be obtained from the do-nothing transition matrix at age t by using the simple transformation shown in Fig. 1.

With these transition matrices, the deterioration rate increases with time, as can be seen in Appendix I. However, when a reconstruction action is applied on the bridge deck, the transition matrices return to their initial values.

The literature only gives the transition matrices until age 54 (Jiang et al. 1989). We created additional transition matrices for bridge ages greater than 55 years, while respecting the structure of the previous matrices. It should be noted that, after age 73, the transition matrices do not depend on time anymore (i.e., they are time-homogeneous), because the deterioration matrix has reached its lower bound.

Constant Transition Matrix over Time

The model was first run with the constant transition matrices for age greater than 73 years. In this case, the deterioration matrix is constant. We can expect that these matrices will have an important impact on the agency's policy for a T-year-cycle optimal policy for large values of T. Thus, a better understanding of the optimal policies for this constant deterioration process will allow a better understanding of the structure of the optimal policy for a long cycle.

In this case the results of the model are trivial. Indeed, whatever the cycle-length may be, the agency does not accrue any savings with the joint maintenance and reconstruction model, because the T-year-cycle steady-state policy for any T is always the juxtaposition of T of the 1-year-cycle steady-state policies. The agency does not benefit from the greater flexibility in utilizing its budget.

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a(1,1)	a(1,2)	0	0	0	0	0	0	0	0
0	a(2,2)	a(2,3)	0	0	0	0	0	0	0
0	0	a(3,3)	a(3,4)	0	0	0	0	0	0
0	0	0	a(4,4)	a(4,5)	0	0	0	0	0
0	0	0	0	a(5,5)	a(5,6)	0	0	0	0
0	0	0	0	0	a(6,6)	a(6,7)	0	0	0
0	0	0	0	0	0	a(7,7)	a(7,8)	0	0
0	0	0	0	0	0	0	a(8,8)	a(8,9)	0
0	0	0	0	0	0	0	0	a(9,9)	a(9,10)
0	0	0	0	0	0	0	0	0	a(10,10)

Do-Nothing Transition Matrix at Age t

a(1,1)	a(1,2)	0	0	0	0	0	0	0	0
a(1,1)	a(1,2)	0	0	0	0	0	0	0	0
0	a(2,2)	a(2,3)	0	0	0	0	0	0	0
0	0	a(3,3)	a(3,4)	0	0	0	0	0	0
0	0	0	a(4,4)	a(4,5)	0	0	0	0	0
0	0	0	0	a(5,5)	a(5,6)	0	0	0	0
0	0	0	0	0	a(6,6)	a(6,7)	0	0	0
0	0	0	0	0	0	a(7,7)	a(7,8)	0	0
0	0	0	0	0	0	0	a(8,8)	a(8,9)	0
0	0	0	0	0	0	0	0	a(9,9)	a(9,10)

Rehabilitation Transition Matrix at Age t

FIG. 1. Development of Rehabilitation Matrices from Do-Nothing Matrices

W_{ai} (optimal fraction of facilities which are in state i and to which action a is applied)

state	1	2	3	4	5	6	7	8	9	10
do-nothing	0.1	0	0	0	0	0	0	0	0	0
rehabilitation	0	0.9	0	0	0	0	0	0	0	0

Budget Required: $2.70 per square yard per year

FIG. 2. Optimal Maintenance-Only Policy under Constant Transition Matrices

As can be seen in Fig. 2, the optimal steady-state policy does not include any improvement action. This means that to allocate a specific budget for improvements is somewhat absurd, because it is cheaper to maintain the network in a good state with maintenance actions. The optimal policies with the constant transition matrix are presented in Fig. 2, where the budget required is in dollars per square yard per year.

Every year in this steady-state policy, the agency does nothing on the parts of bridge decks in State 1 (10%), and it rehabilitates the parts of bridge decks in State 2 (90%). Actually, the same optimal policy is found when using any transition matrix for ages 25 years or older. Therefore, this steady-state policy is the optimal way to maintain a network of bridge decks whose transition matrices would be constant and equal to any of the transition matrices of our study for ages greater than 25 years. Intuitively, this means that this policy should start to have an impact on the *T*-year-cycle optimal strategy very quickly as *T* increases. We will analyze this impact in a later section.

Maintenance-Only Policy

With the time-dependent transition matrices presented in Appendix I, the network can be maintained (i.e., kept out of the unacceptable states) without any reconstruction. While this policy may appear unrealistic, we studied this possibility that will turn out to be suboptimal.

In a *T*-year-cycle steady state, the state at year $k + T$ is the same as the state at year k; similarly, for any N, the state at year $k + NT$ is the same as the state at time $k + (N - 1)T$. It is possible to choose N to be large enough so that $(N - 1)T$ is larger than 73 years, which is the age at which the transition matrices are constant. Therefore, it is possible to obtain a steady-state policy for any cycle length T, based on the constant transition matrices corresponding to ages greater than 73 years. This optimal steady-state policy is the one described in the previous section, and has a cost of $2.70 per square yard per year.

Strategy with Reconstruction and Dynamic Budget Management

We now study the joint maintenance and reconstruction policies. Because the state after a reconstruction is exactly the state when the bridge deck is new, we need to study the optimal policy with exactly one reconstruction for a given T. Without loss of generality, we assume that the first state of the cycle is the state of a new bridge (just after the reconstruction).

For every T (length of the cycle), we need only solve for the optimal cycle, which begins with a reconstruction (new deck) and ends just before another reconstruction, and with no other reconstruction inside the cycle. The only constraints are transition constraints and quality constraints. Thus, we obtain one optimal policy for every cycle length (if a feasible policy exists for this cycle length), and we compare these different optimal cycles by calculating the average cost per year of the cycle. One should note that if a T-year cycle is not feasible, then any $T + u$-year cycle, where $u > 0$, is not feasible either. Fig. 1 presents the optimal average cost per year for different cycle lengths T.

The two dashed curves in Fig. 3 explain the structure of the T-year-cycle optimal policy for small and large values of T: For small values of T, the cost of maintenance actions for the

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cycle is negligible before reconstruction, because the bridge deck has not deteriorated much. Therefore, as can be seen on the graph, the annual cost of the optimal policy is about

$$\frac{\text{Cost of Reconstruction}}{T} = \frac{60}{T}$$

(which is the lower dashed curve). For large values of T, we can separate the costs before and after year 25 of the cycle. If C_t is the cost at year t, we have

$$\text{Average Annual Cost} = \frac{\sum_{t=1}^{24} C_t}{T} + \frac{\sum_{t=25}^{T-1} C_t + 60}{T}$$

As T increases, because C_t has an upper bound, the first part of this expression becomes negligible and the optimal solution consists of minimizing the costs after year 25. We saw previously that the best policy for ages greater than 25 years was the steady-state policy with a cost of \$2.70 per square yard per year. Therefore, for large values of T, we expect the optimal policy to be as follows:

1. Year 1 to 24: The best strategy is to get the network in State 1 or 2 at year 24. The optimal solution gives a cost of \$32.70 per square yard for 24 years.
2. Year 25 to $T - 6$: An optimal policy with a cost of \$2.70 per square yard per year.
3. Year $T - 5$ to $T - 1$: Do-nothing; therefore, the cost is zero (we can let the network deteriorate because there is a reconstruction at year T).
4. Year T: Reconstruction whose cost is \$60 per year per square yard.

Therefore, we have

$$\text{Average Annual Cost} = \frac{32.70}{T} + \frac{(T - 30) \times 2.70 + 5 \times 0 + 60}{T} = 2.70 + \frac{11.70}{T}$$

This is the top dashed curve. We observe that it fits the minimum cost curve quite well for large values of T.

Strategy with Reconstruction and Static Budget Management

One can see in Fig. 3 that the optimal policy is found for a cycle time of 50 years. We now study more precisely the op-

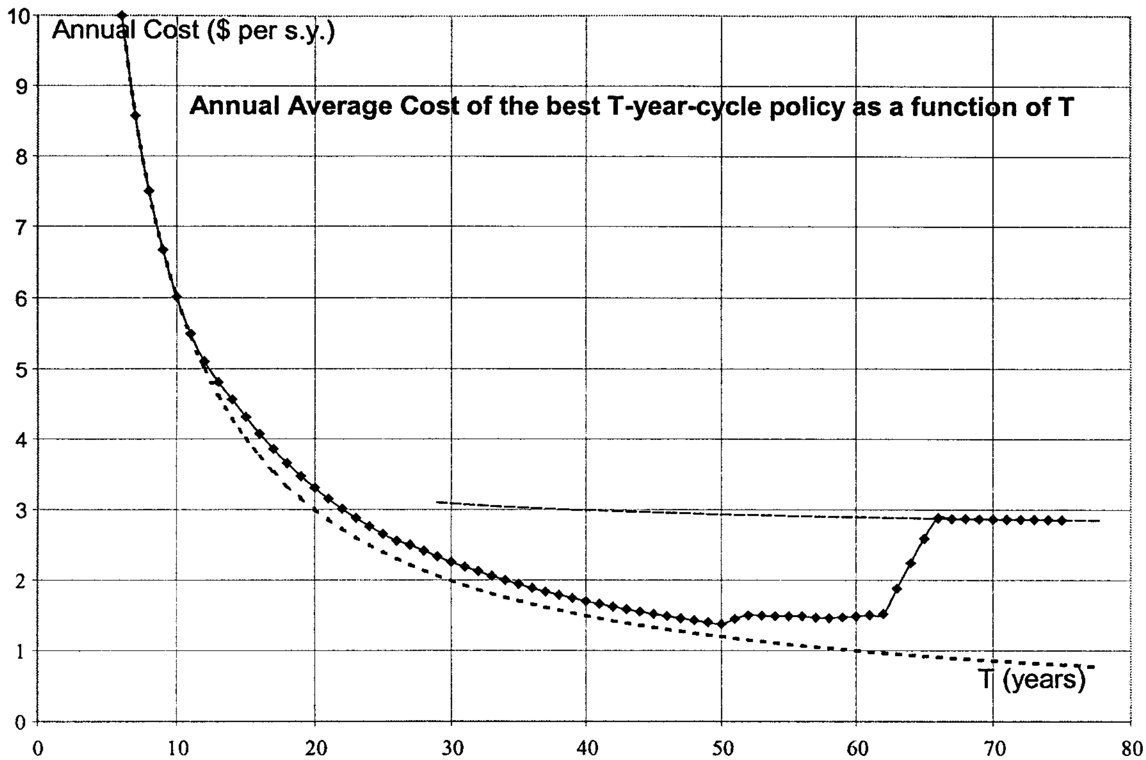

FIG. 3. Dynamic Budget Policy

Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13
0.93	0.93	0.93	0.93	0.93	0.93	0.00	0.00	0.10	0.32	0.00	0.00	0.16
Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20	Year 21	Year 22	Year 23	Year 24	Year 25	
0.05	0.06	0.08	0.10	0.12	0.14	0.11	0.13	0.14	0.15	0.17	0.18	
Year 26	Year 27	Year 28	Year 29	Year 30	Year 31	Year 32	Year 33	Year 34	Year 35	Year 36	Year 37	Year 38
0.10	0.10	0.10	0.11	0.11	0.00	0.00	0.01	0.01	0.02	0.03	0.03	0.04
Year 39	Year 40	Year 41	Year 42	Year 43	Year 44	Year 45	Year 46	Year 47	Year 48	Year 49	Year 50	
0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.07	0.08	0.09	0.09	60.00	

FIG. 4. Annual Budget (in Dollars per Square Yard) for Each Year of Optimal Maintenance Policy

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timal steady-state cycle, whose annual budgets are given in Fig. 4. We observe that the budget spent for maintenance is not constant over time.

This means that it is worth adopting a dynamic budget management, which is not very surprising. It is interesting to quantify the gains that can be obtained thanks to this dynamic budget management. To do so, we repeated the same optimization, but with a new objective function: Minimize the maximum of the T maintenance budgets. The constraints are the same as previously (transition constraints, quality constraints, the first state of the cycle is the state of a new bridge deck). This optimization allows us to find the minimum annual maintenance budget needed by an agency given the constraints.

To find the total budget required for a static budget management, we add the budget for maintenance, which is the value of the new objective function at optimality multiplied by $(T - 1)$ to the budget for reconstruction ($60.00 per square yard every T years). Fig. 5 summarizes the results obtained with both the dynamic and the static budget management policies.

As expected, the static budget management cost curve lies

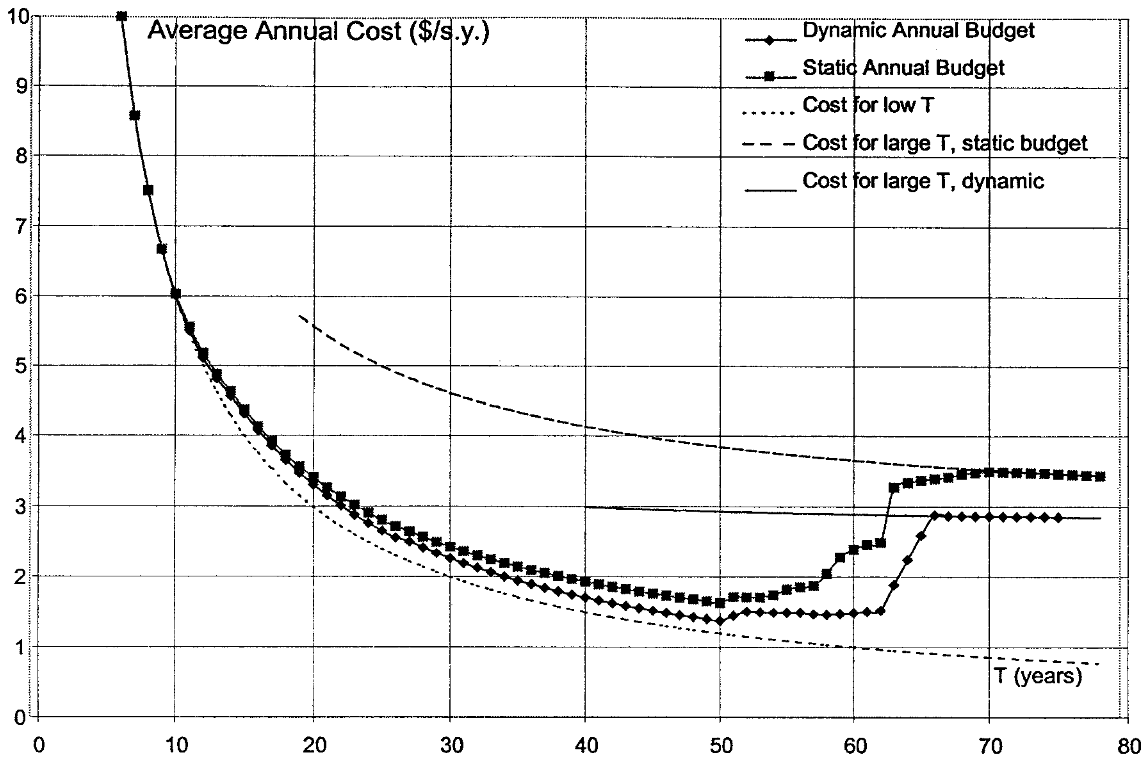

FIG. 5. Comparison of Static and Dynamic Budget Management Policies

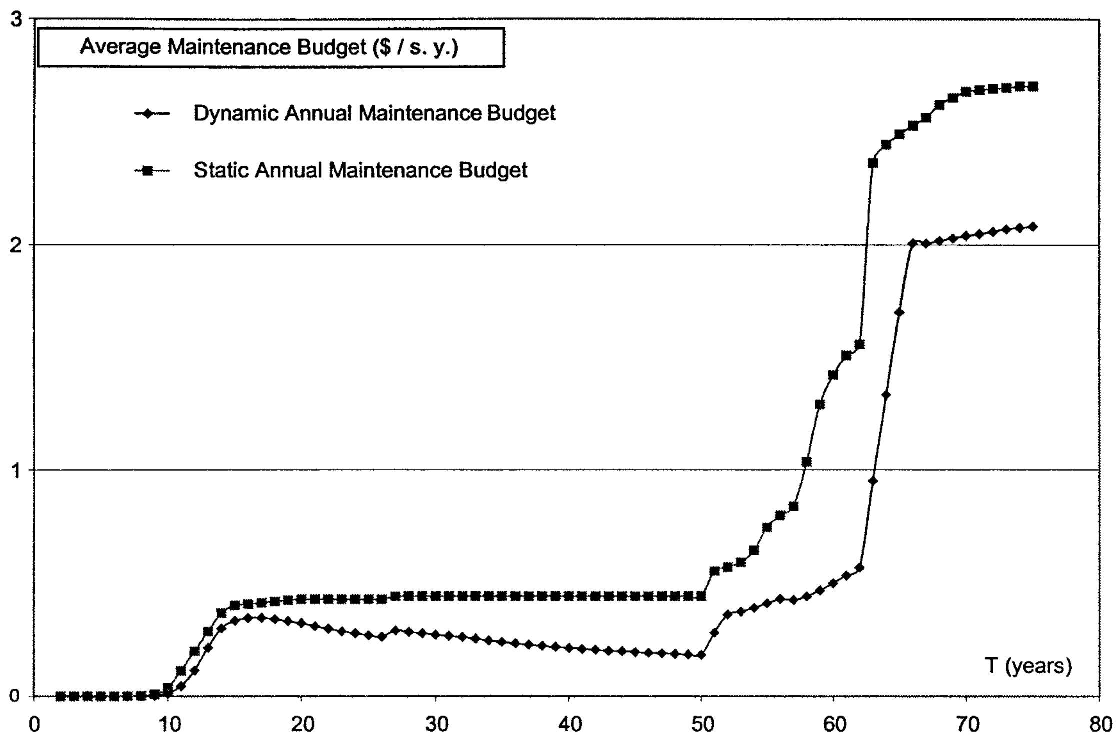

FIG. 6. Annual Average Maintenance Budget, Dynamic, and Static Policies

TABLE 1. Comparison of Minimum Annual Average Cost for Three Models

(1)	Maintenance only (2)	Dynamic budget (3)	Static budget (4)
Best cycle length	n/a[a]	50	50
Maintenance budget (dollars per square yard)	n/a[a]	8.91	21.67
Average annual budget (dollars per square yard)	2.70	1.38	1.63

Note: Cycle length: Value of T. Maintenance budget: Total budget spent in maintenance actions from year 1 to year $T - 1$ in cycle. Average annual budget (for the two joint optimization policies): (Maintenance budget $+60)/T$.

[a]Not applicable.

above the curve corresponding to the dynamic budget management. The static budget management annual cost, for large values of T, shown as a dashed line in Fig. 5, is easily explained

$$\text{Average Annual Cost} = \frac{2.70 \times (T - 1) + 60}{T}$$

Some additional remarks should be made at this point:

- While the dynamic budget management method achieves lower cost, the optimal cycle lengths for the dynamic and static budget management are the same.
- The minimum cost functions have the same behavior with T.

These abrupt changes of the average annual costs with T reflect the fact that the network has to be maintained in an acceptable state, and that the maintenance costs are discrete. For instance, for very low values of T, the agency does not have to spend any money on maintenance because the bridge decks will not have enough time to deteriorate to the nonacceptable states before the reconstruction. The maintenance cost will be zero and the average annual total cost will be $60/T$. But there will be a T for which a bridge deck does not have the time to deteriorate to the nonacceptable states; at this point, the do-nothing-every-year policy is not feasible anymore. For this value of T, the maintenance costs will become nonzero and a steep change will occur. In fact, every abrupt change occurs when such a feasibility problem is encountered, increasing significantly the maintenance costs as shown in Fig. 6. Because the feasibility problems are the same for the dynamic and static budget management, we can expect the optimal cycle lengths to be close to one another.

Table 1 summarizes the results of the case study. Two conclusions can be drawn. The first conclusion is that the joint optimization of maintenance and improvement policies leads to substantial cost savings. For the dynamic budget policy, the average annual costs are about 49% lower than those corresponding to the maintenance-only policy. These savings are achieved because the agency is able to combine improvement and maintenance actions optimally for the purpose of minimizing costs, rather than having to depend exclusively on maintenance activities. The second conclusion is that relaxing the constraint of constant budget utilization is advantageous. The cost implication of using dynamic budget management is significant: As Table 1 indicates, the annual average cost with the dynamic budget policy is 19% lower than with static budget management.

CONCLUSIONS

The purpose of this research was to develop an optimization model that would integrate infrastructure maintenance and improvement policies. The motivation for this work was that trade-offs exist between maintenance and improvement policies, and so it may be inefficient to optimize these two sets of actions independently.

A new steady-state model was developed to take this issue into account, and a case study on a hypothetical network of bridge decks was performed. The results show the following:

- Significant savings can be accrued by using such a joint optimization approach.
- Further savings can be achieved by adopting dynamic budget management.

The joint optimization model presented herein did not account for all of the benefits of facility improvement, such as safety enhancement and congestion reduction, because the focus of this paper was on condition-state. It must be emphasized that highway agencies consider all of these criteria jointly when selecting improvement policies, whereas our model assumed that improvement decisions were dictated only by condition-state considerations. It is therefore important to recognize that in the real world the applicability of our model may be restricted by noncondition criteria.

The finite horizon model required to take the network from an initial condition distribution to the optimal steady-state distribution was not studied in this paper. As mentioned previously, the short-term problem consists of minimizing the cost to reach the steady-state in a given finite horizon, and optionally, of finding the optimal finite horizon. This problem was not studied because the model introduced herein focuses on long-term savings and steady-state policies. Nevertheless, the development of the corresponding short-term model does not appear to present any new insights.

One limitation of the research presented herein is that some of the models used in the case study may not be realistic. Specifically, the bridge deck condition transition matrices under maintenance were synthetic, rather than estimated from field data. This limitation was due to the fact that we did not find empirical maintenance transition matrices for bridge decks in the literature. In the absence of such information, the best that can be done would be to analyze the sensitivity of our results with respect to the assumed maintenance matrices. While we did not perform a systematic sensitivity analysis, we predict that changes in the maintenance transition probabilities will affect the optimal policies and the minimum annual cost, but not the overall conclusion. The joint optimization of maintenance and replacement policies will continue to produce lower average annual costs than that of the maintenance-only policy. This can be explained as follows: If the maintenance transition probabilities from one state to lower states are increased (i.e., if maintenance becomes less effective), then both policies will become more expensive. However, the effect on the maintenance-only policies will be to increase average annual cost, while the effect on the joint optimization policy will be to shorten the optimal cycle length. In other words, the effect of the reduction in maintenance effectiveness on annual cost will be less for the joint optimization because it has one additional degree of freedom in responding to it. On the other hand, if the maintenance transition probabilities from one state to lower states are decreased (i.e., if maintenance becomes more effective), then both policies will become less expensive. However, the effect on the maintenance-only policies will be to reduce the average annual cost, while the effect on the joint policy will be to lengthen the optimal cycle length. But only at the limit will it become optimal to never replace and depend only on maintenance ($T \rightarrow \infty$), in which case the joint policy will be equivalent to the maintenance-only policy. In other words, the joint policy cannot do worse than the maintenance-only policy.

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APPENDIX I. COSTS AND TRANSITION MATRICES

COSTS ($ per square yard)

Maintenance	Do-nothing	0	0	0	0	0	0	0	0	0	0
	Rehabilitation	0.5	3.0	8.5	16.5	43.5	53.5	55.5	57.0	58.0	58.5
Improvement	Do-nothing	0	0	0	0	0	0	0	0	0	0
	Reconstruction	60	60	60	60	60	60	60	60	60	60

Do-Nothing Transition Matrices / ***Rehabilitation Transition Matrices***

Age 1 to 6

Do-Nothing

0.69	0.31	0	0	0	0	0	0	0	0
0	0.77	0.23	0	0	0	0	0	0	0
0	0	0.92	0.08	0	0	0	0	0	0
0	0	0	0.91	0.09	0	0	0	0	0
0	0	0	0	0.9	0.1	0	0	0	0
0	0	0	0	0	0.79	0.21	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	1

Rehabilitation

0.69	0.31	0	0	0	0	0	0	0	0
0.69	0.31	0	0	0	0	0	0	0	0
0	0.77	0.23	0	0	0	0	0	0	0
0	0	0.92	0.08	0	0	0	0	0	0
0	0	0	0.91	0.09	0	0	0	0	0
0	0	0	0	0.9	0.1	0	0	0	0
0	0	0	0	0	0.79	0.21	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0

Age 7 to 12

Do-Nothing

0.42	0.58	0	0	0	0	0	0	0	0
0	0.86	0.14	0	0	0	0	0	0	0
0	0	0.86	0.14	0	0	0	0	0	0
0	0	0	0.69	0.31	0	0	0	0	0
0	0	0	0	0.72	0.28	0	0	0	0
0	0	0	0	0	0.56	0.44	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	1

Rehabilitation

0.42	0.58	0	0	0	0	0	0	0	0
0.42	0.58	0	0	0	0	0	0	0	0
0	0.86	0.14	0	0	0	0	0	0	0
0	0	0.86	0.14	0	0	0	0	0	0
0	0	0	0.69	0.31	0	0	0	0	0
0	0	0	0	0.72	0.28	0	0	0	0
0	0	0	0	0	0.56	0.44	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0

Age 13 to 18

Do-Nothing

0.65	0.35	0	0	0	0	0	0	0	0
0	0.91	0.09	0	0	0	0	0	0	0
0	0	0.91	0.09	0	0	0	0	0	0
0	0	0	0.92	0.08	0	0	0	0	0
0	0	0	0	0.97	0.03	0	0	0	0
0	0	0	0	0	0.76	0.24	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	1

Rehabilitation

0.65	0.35	0	0	0	0	0	0	0	0
0.65	0.35	0	0	0	0	0	0	0	0
0	0.91	0.09	0	0	0	0	0	0	0
0	0	0.91	0.09	0	0	0	0	0	0
0	0	0	0.92	0.08	0	0	0	0	0
0	0	0	0	0.97	0.03	0	0	0	0
0	0	0	0	0	0.76	0.24	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0

Age 19 to 24

Do-Nothing

0.1	0.9	0	0	0	0	0	0	0	0
0	0.07	0.93	0	0	0	0	0	0	0
0	0	0.96	0.04	0	0	0	0	0	0
0	0	0	0.95	0.05	0	0	0	0	0
0	0	0	0	0.98	0.02	0	0	0	0
0	0	0	0	0	0.93	0.07	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	1

Rehabilitation

0.1	0.9	0	0	0	0	0	0	0	0
0.1	0.9	0	0	0	0	0	0	0	0
0	0.07	0.93	0	0	0	0	0	0	0
0	0	0.96	0.04	0	0	0	0	0	0
0	0	0	0.95	0.05	0	0	0	0	0
0	0	0	0	0.98	0.02	0	0	0	0
0	0	0	0	0	0.93	0.07	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0

Age 25 to 30

Do-Nothing

0.1	0.9	0	0	0	0	0	0	0	0
0	0.1	0.9	0	0	0	0	0	0	0
0	0	0.94	0.06	0	0	0	0	0	0
0	0	0	0.98	0.02	0	0	0	0	0
0	0	0	0	0.99	0.01	0	0	0	0
0	0	0	0	0	0.11	0.89	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	1

Rehabilitation

0.1	0.9	0	0	0	0	0	0	0	0
0.1	0.9	0	0	0	0	0	0	0	0
0	0.1	0.9	0	0	0	0	0	0	0
0	0	0.94	0.06	0	0	0	0	0	0
0	0	0	0.98	0.02	0	0	0	0	0
0	0	0	0	0.99	0.01	0	0	0	0
0	0	0	0	0	0.11	0.89	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0

Age 31 to 36

Do-Nothing

0.1	0.9	0	0	0	0	0	0	0	0
0	0.1	0.9	0	0	0	0	0	0	0
0	0	0.99	0.01	0	0	0	0	0	0
0	0	0	0.98	0.02	0	0	0	0	0
0	0	0	0	0.95	0.05	0	0	0	0
0	0	0	0	0	0.99	0.01	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0
0	0	0	0	0	0	0	0	0	1

Rehabilitation

0.1	0.9	0	0	0	0	0	0	0	0
0.1	0.9	0	0	0	0	0	0	0	0
0	0.1	0.9	0	0	0	0	0	0	0
0	0	0.99	0.01	0	0	0	0	0	0
0	0	0	0.98	0.02	0	0	0	0	0
0	0	0	0	0.95	0.05	0	0	0	0
0	0	0	0	0	0.99	0.01	0	0	0
0	0	0	0	0	0	0.5	0.5	0	0
0	0	0	0	0	0	0	1	0	0
0	0	0	0	0	0	0	0	1	0

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APPENDIX I. *Continued*

37 to 42	0.1	0.9	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0	0.83	0.17	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0
	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.83	0.17	0	0	0	0	0	0
	0	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.99	0.01	0	0	0	0	0
	0	0	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0.99	0.01	0	0	0
	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.5	0.5	0	0
	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
43 to 48	0.1	0.9	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0	0.57	0.43	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0
	0	0	0	0.92	0.08	0	0	0	0	0	0	0	0.57	0.43	0	0	0	0	0	0
	0	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.92	0.08	0	0	0	0	0
	0	0	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.95	0.05	0	0	0	0
	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0.99	0.01	0	0	0
	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.5	0.5	0	0
	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
49 to 54	0.1	0.9	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0
	0	0	0	0.55	0.45	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0
	0	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.55	0.45	0	0	0	0	0
	0	0	0	0	0	0.48	0.52	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0.48	0.52	0	0	0
	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.5	0.5	0	0
	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
55 to 60	0.1	0.9	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0
	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0
	0	0	0	0	0.55	0.45	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0
	0	0	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.55	0.45	0	0	0	0
	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0.95	0.05	0	0	0
	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.5	0.5	0	0
	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
61 to 66	0.1	0.9	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0
	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0
	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0
	0	0	0	0	0	0.55	0.45	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0
	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0.55	0.45	0	0	0
	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.5	0.5	0	0
	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
67 to 72	0.1	0.9	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0
	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0
	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0
	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0
	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0	0.1	0.9	0	0	0
	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.5	0.5	0	0
	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0
73 to …	0.1	0.9	0	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0
	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0
	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0
	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0
	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0	0
	0	0	0	0	0	0	0.1	0.9	0	0	0	0	0	0	0	0.1	0.9	0	0	0
	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.1	0.9	0	0
	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0

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