Network-Level Analysis of Staged Pavement Rehabilitation and Reconstruction

VERA MIJUSKOVIC, DRAGAN BANJEVIC, AND GORAN MLADENOVIC

An analysis of the influence of the staged construction on the overall network condition was performed. It investigates the relations between strategies concerning the sequence of rehabilitation works for one-step and staged construction. The road network pavement deterioration and repair were described by means of a controlled nonhomogeneous Markov process. The influence of initial network condition on final condition and users' costs for both one-step and staged construction was studied. It was concluded that the basic relations between strategies for one-step construction remained unchanged in the case of staged construction. Also, there was no difference between the effects considered (backlog, extra users' costs and extra routine maintenance costs) of two types of construction in the first 15 years of a 20-year design period. No reason has been found to improve a greater part of network by measures of shorter service life instead of improving a minor part of network by measures of longer service life.

Quality improvements of a road network in very poor condition are usually limited by budgetary constraints. Although project-level analysis, based on life-cycle costs, has indicated that staged construction is not profitable, highway officials are often forced into repairs with shorter service lives and postponement of achieving excellent condition. Other studies have proved that "what is the best for the section must not be the best for the whole network" (*1,2*). Thus, the basic aim of investigations described hereafter was to compare the network-level effects of two ways of producing a high-quality pavement: one-step and staged construction.

The network-level pavement performance prediction model, used to describe the interdependence between pavement quality and preservation strategy for one-step construction, has already been presented in previous studies (*3,4*). Only the basic characteristics needed to understand the adaptations made for staged construction simulation will be presented herein. Since the model deals with strategies defined as principles, it is as simple as possible. For practical use, it has to be widened and calibrated.

MODEL DESCRIPTION FOR ONE-STEP CONSTRUCTION

Road networks are classified according to pavement type, pavement width, design period, and traffic volume. Pavement condition on the part of a network of the same type, same width, and in *k*th class of traffic volume in a year *i* is described by *state vector* α_k^i:

$$\alpha_k^i = \left[\alpha_{10,k}^i \; \alpha_{11,k}^i \; \alpha_{12,k}^i \; \alpha_{20,k}^i \; \alpha_{21,k}^i \; \alpha_{3,k}^i \; \alpha_{4,k}^i\right] \quad (1)$$

where

$\alpha_{10,k}^i$ = the contribution of new, strengthened, and reconstructed road sections in excellent state;
$\alpha_{11,k}^i$ = the contribution of new, strengthened, and reconstructed road sections in excellent state after one treatment with a thin layer;
$\alpha_{12,k}^i$ = the contribution of new, strengthened, and reconstructed road sections in excellent state after two treatments with thin layers;
$\alpha_{20,k}^i$ = the contribution of new, strengthened, and reconstructed road sections without surface treatment in good state;
$\alpha_{21,k}^i$ = the contribution of new, strengthened, and reconstructed road sections with one thin layer in good state;
$\alpha_{3,k}^i$ = the contribution of roads in fair state; and
$\alpha_{4,k}^i$ = the contribution of roads in poor state.

Pavement condition classes are delimited by values of any index or group of indicators that serve as standards for particular types of interventions.

Another group of *s* vectors describes the percentile distribution of road length, in particular age classes with an increment of 1 year, separately for originally constructed pavement and separately for every type of improvement (Figure 1).

There are three types of interventions aimed at bringing the pavement into excellent condition:

- Improvement from good to excellent condition by applying surface treatment or thin layers (whose minimum and maximum depths depend on traffic load class or constructibility);
- Improvement from fair to excellent condition by rehabilitation; and
- Improvement from poor to excellent condition by reconstruction.

Markov processes are used to forecast pavement deterioration on the entire network. As there are only four pavement condition categories for which excellent condition comprised a long period on the rating plot, inhomogeneous chains were chosen. To treat deterioration and repair as parts of a unique process, controlled chains

V. Mijuskovic, Faculty for Traffic and Transport Engineering, University of Belgrade, Vojvode Stepe 305, 11000 Belgrade, Yugoslavia. D. Banjevic, University of Toronto, 100 St. George Street, Toronto, Ontario M5F1A1. G. Mladenovic, Civil Engineering Faculty, University of Belgrade, Bulevar Revolucije 73, 11000 Belgrade, Yugoslavia.

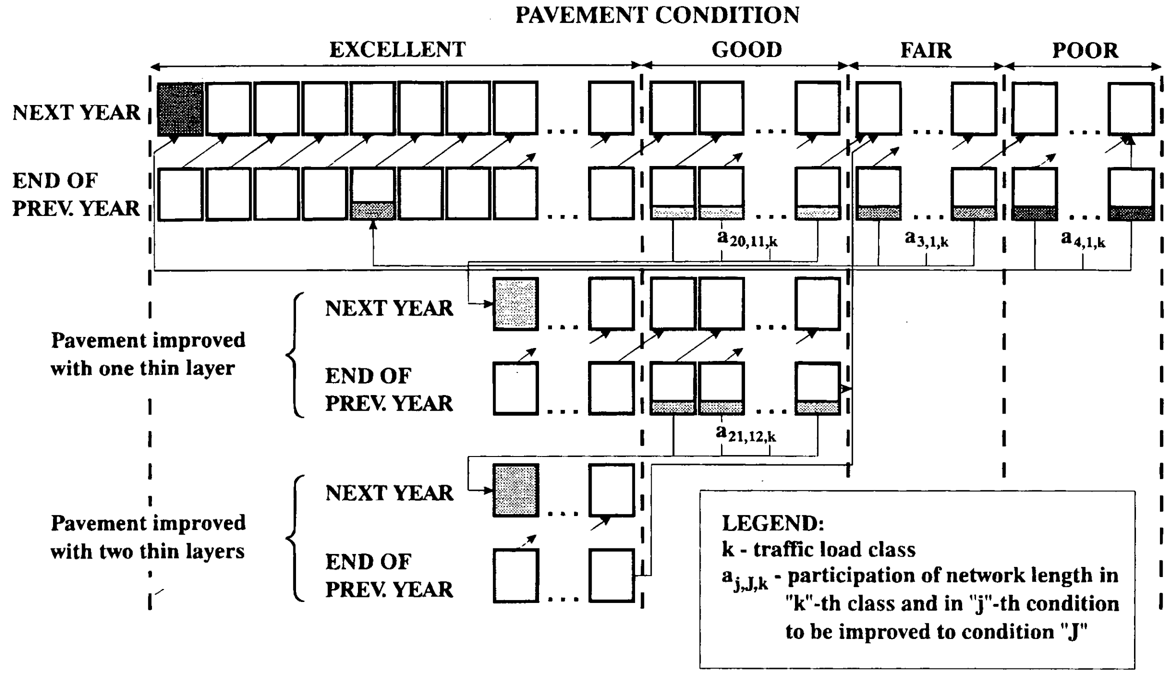

FIGURE 1 Calculation of transition probabilities based on age vectors.

were adopted. The probabilities needed for the transition matrix are calculated for every year by summing the corresponding classes of the age vectors. There is no obstacle to introducing semi-Markov processes if the required data are available. Six strategies concerning priorities were considered. Four of them were with fixed priorities, and two were with optimal choice according to investor's and users' points of view. The quantity of repair work was determined in the frame of the given equal or unequal amounts of annual budget. Six strategies were considered:

1. *Best-first*—sections in good condition are improved first followed by sections in fair and poor condition;
2. *Proportional*—the length of repaired roads is in proportion to their contribution in particular condition classes;
3. *Involving standards*—the part of the road length under the allowed quality standards is improved first, the remaining budget is spent according to the best-first strategy;
4. *Worst-first*—sections in poor condition are improved to excellent condition, followed by sections in fair condition, and finally sections in good condition;
5. *Optimal investor's*—the priority sequence is defined by optimization according to the "minimal backlog" criterion, where backlog represents the total needed to bring the entire network into excellent condition in 1 year;
6. *Optimal users'*—the priority sequence is defined by optimization according to the criterion of minimal extra users' costs caused by imperfect pavement condition.

The second and the third strategy have only practical meaning, so only the results of the first, fourth, fifth, and sixth are presented in the paper.

Three different indicators of effects for every strategy mentioned above have been considered.

Backlog

Backlog represents the total needed to improve the entire network to an excellent condition. The general idea of backlog as a measure of effects was taken from Bates's pavement management forecasting (PMF) model (*5*). Compared with the other criteria used in the network-level optimization systems, backlog has some advantages that must be respected:

- It is easily understandable to decision makers who are not experts in highway engineering;
- Savings in backlog can be discounted during the analysis period and added to other types of savings (i.e., the profitability indicators may be calculated); and
- It is very convenient for the optimization process.

Extra Users' Costs

Extra users' costs are additional costs caused by nonperfect condition of pavement surface. The basic target of any traffic network improvement is to lower transportation costs. We also must be aware that these costs are dispersed on millions of users and automatically incorporated in the price of every article, while it is extremely difficult for the road manager to generate the money from different sources. This is probably why vehicle operating costs are not included in many pavement management systems. They exist mostly in the systems developed by the World Bank as well as several European countries, such as Norway and Finland (*6*). In 1987, the Organization for Economic Cooperation and Development (OECD) Scientific Expert Group for Pavement Management (*7*) "recognize[d] that user costs are an important factor in economic analysis, [but] it is common practice to exclude all or part of these costs from decision-making models for the following reasons:

—Precise quantitative data [are] not presently available
—Extremely high relative level of these costs may lead to maintenance norms being selected that are incompatible with budget constraints . . .
—Reduction in users' costs does not necessarily lead to an increase in the funds available for maintenance . . . .

"The . . . serious omission in most existing pavement management methods is their apparent failure to specify a quantifiable statement of goals and objectives that compares the positive and negative impacts of pavement states, intervention levels, and technique on all concerned parties—i.e., highway authorities, users and community at large. . . . Particularly important is the lack of consideration given to quantifying the impacts on users' costs of pavement management decisions."

We had in mind several facts when deciding to introduce these costs. (a) Extensive investigations have been performed in this field from the time this report was written and their results were successfully implemented. (b) The definition of total life-cycle costs of a highway project in European and World Bank contractor countries comprises costs of investment (initial construction), maintenance (routine maintenance plus reinvestment, i.e., rehabilitation), users' costs (time, operating, discomfort), and social costs (traffic disruption, accident and environmental costs). Different countries use different numbers for these particular costs according to the extent and accuracy of their data banks. (c) The criteria for the network-level management must be as close as needed to the project level if we consider both as stages and accuracy levels of a unique process. (d) These costs may be decisive by choosing the sections when all the other effects are equal.

We neglected some redistribution of traffic caused by improvement of pavement quality and assumed that only changes in costs due to changes in roughness and slipperiness are decisive for the rehabilitation strategies. Thus, we calculated the increase in vehicle operating costs related to the costs on a harsh and even pavement by means of vehicle operating cost (VOC) Module 4 of HDM-III (*8*). Using only the additional users' costs, we hope to overcome an eventual error caused by the inconvenience of the VOC module for the saturated traffic flows that we also considered.

Extra Routine Maintenance Costs

Occasionally, additional expenditures related to the costs of the routine maintenance of excellent pavement are needed to provide the viability without improving its condition. The proportion between routine maintenance costs for pavements in particular condition categories is almost the same as that between corresponding rehabilitation costs, so the priority sequence is the same as when backlog is an optimization criterion. How quickly pavement deteriorates depends largely on the routine maintenance level, but no quantification of such relationships was available to us. So they are only one of the effects considered to enable further economic calculations.

The pavement lifetime spent in a particular condition, as well as the service life of repair measures (i.e., pavement performance curves), may be defined by the user. Any deterioration model may be adopted in such a way. The data for pavement lifetime in initial considerations were taken from Bates's PMF model (*5*). The AASHTO and HDM-III curves were included later. The effects shown in this paper are calculated according to PMF data because they correspond to the asphalt concrete HDM-III curve for regional factor cca 0.65, which is not far from the recommendations for our region. The substantial differences we found between the AASHTO and HDM-III performance curves adapted for the same year of failure with the aforementioned regional factor (using the Sayers correlations for roughness) represent two facts: (a) longer service life in excellent condition and (b) some slower deterioration of pavement structure for minor traffic volume, both in the HDM-III model.

Knowing that according to the PMF model the "best-first" strategy was always the best, we searched a set of input data that would possibly give some other priority sequence from any point of view. Thus, we adopted a few hypothetical combinations that represent only a frame in which data could appear. In reality, the highest contributions usually make good pavements.

The combinations adapted are as follows:

- Initial general network condition
  —Good: 65% excel. 20% good 10% fair 5% poor pavement
  —Fair: 25% excel. 25% good 25% fair 25% poor pavement
  —Poor: 5% excel. 10% good 20% fair 65% poor pavement
- Pavement performance curve expressed as a length of service periods spent in particular conditions
  —PMF
  —AASHTO
  —HDM-III ($m = 0.65$)
- Funding levels of $1,200, $2,400, $3,600, $4,800, and $6,000/km/year. For a funding level of $2,400/km/year the following alternatives were considered:
  —$2,400 $/km/year
  —$4,800/km every second year
  —$7,200/km every third year

Backlog functions as a consequence of different pavement rehabilitation strategies on the poor network are presented in Figure 2. The optimal users' strategy is identical to the best-first strategy; optimal investor's provides slightly better results. The step-by-step

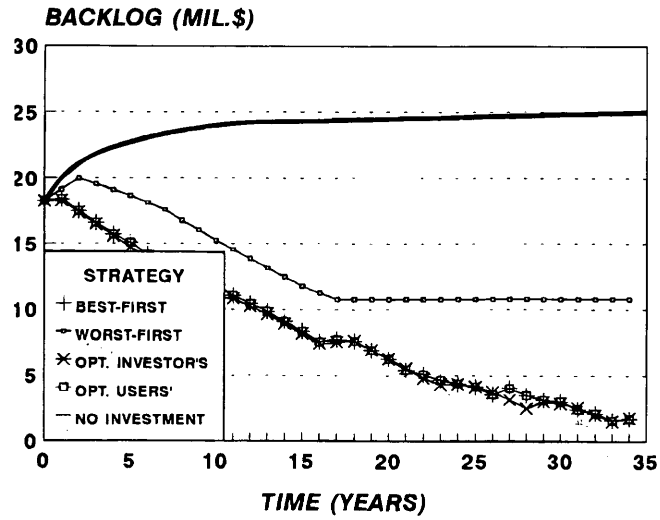

FIGURE 2 Backlog for $3,600/km/year budget as a function of different strategy implementations.

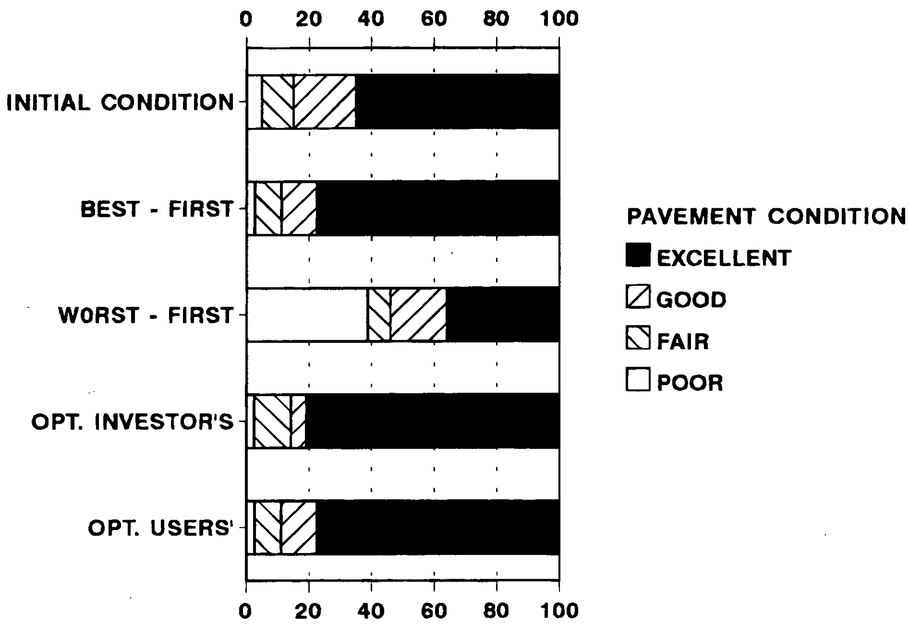

FIGURE 3 Pavement condition for $3,600/km/year budget as a function of different strategy implementations.

analysis showed that sections in fair condition are given first priority under the investor's strategy. Though backlog is almost the same for the three better strategies, pavement condition obtained by those strategies is quite different (Figure 3).

Figures 4 and 5 show backlog and extra users' costs, respectively, depending on strategy and initial network condition. The shape and general orientation of both effects are the same. Whatever the initial network condition, after a long enough period they will have the same values depending only on the budget level. The ninth year of the good network function is interesting for managers; a serious investment must be made at this time. The effects of different budgeting levels are presented in Figure 6.

Based on results of strategy comparison for one-step construction, several general conclusions were reached.

- The effects of the best-first, optimal investor's, and optimal users' strategies are very close; the differences are under the level of accuracy for the model itself.
- The effects of the worst-first strategy are much worse than the effects of the other three strategies (Figures 2 and 3), and the steady

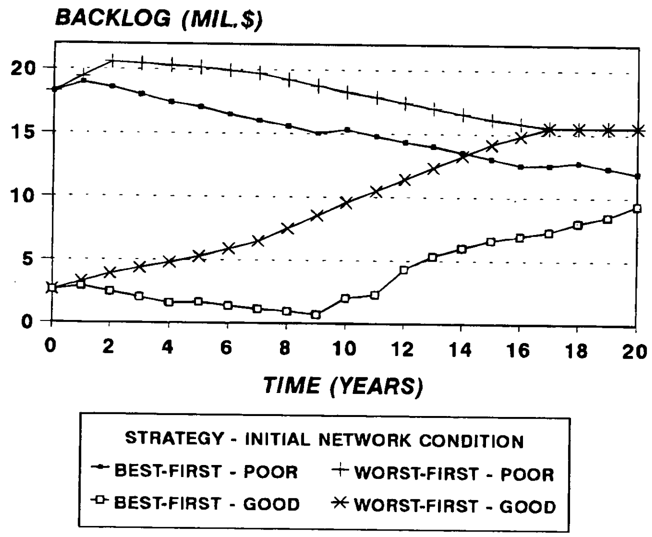

FIGURE 4 Backlog for $2,400/km/year budget and different initial network conditions.

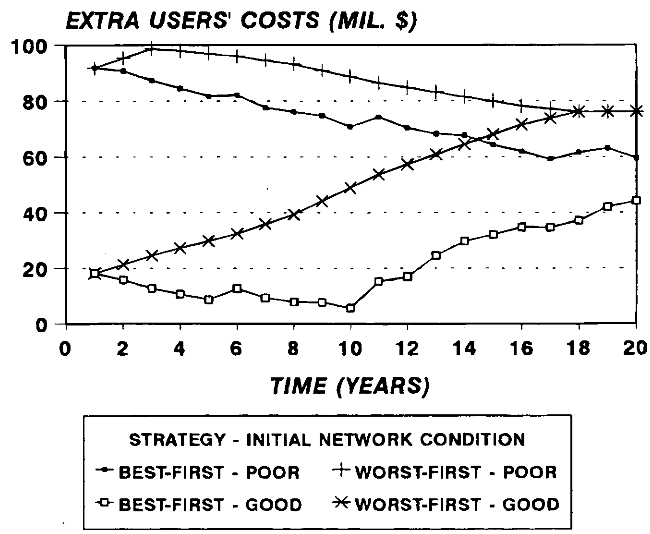

FIGURE 5 Extra users' costs for $2,400/km/year budget and different initial network conditions.

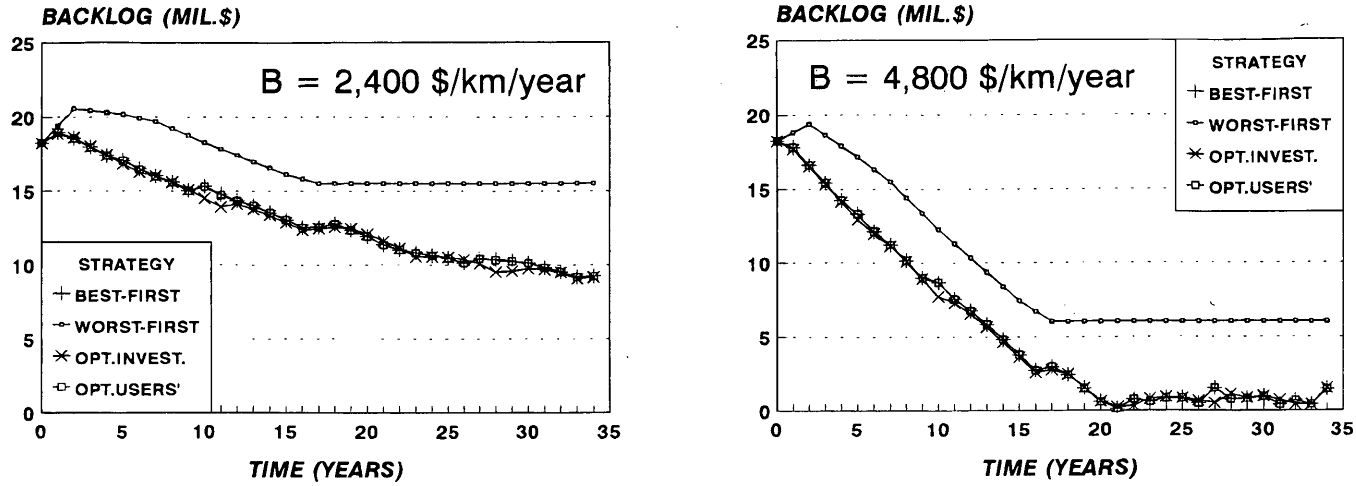

FIGURE 6 Influence of budget level on poor initial network condition.

state begins after the service life of "the youngest" pavement has expired.

- The initial network state has no great influence on the state after 10 years; the available resources are decisive (Figures 4–6).
- Backlog is the most favorable criterion.

It must be pointed out that in the steady state process, no improvement can be expected without additional resources.

ADAPTATION OF MODEL TO STAGED CONSTRUCTION

Two types of questions dealing with the staged construction must be answered:

- Are the effects of staged construction better or worse than those of one-step construction when considered at the network level? and
- Have the strategies been numbered before the same priority sequence as in one-step construction?

Staged construction is more difficult to define at the network level than at the project level. In this study, staged construction was defined as *raising the quality level in two steps. In the first step, all the segments in fair and poor condition are brought into good condition by repair measures with shorter service lives; in the second step, they are brought from good to excellent condition by measures that substantially prolong the pavement lifetime.* For this purpose, the network state vector and the transition matrix were enlarged with the separate class ($\alpha^i_{J3,k}$) for the first step interventions. A limitation was imposed so that the improvement from good to excellent condition could be performed after all the other repairs had been accomplished. In the meantime, all sections deteriorate according to the defined functions and are subjected to routine maintenance measures. The transition matrix appears as follows:

$$\begin{bmatrix} P^i_{10,k} & & & & 1-P^i_{11,k} & & & \\ & P^i_{11,k} & & & 1-P^i_{11,k} & & & \\ & & P^i_{12,k} & & & & 1-P^i_{12,k} & \\ a^i_{13,k} & & & P^i_{13,k}(1-a^i_{13,k}) & (1-P^i_{13,k})(1-a^i_{13,k}) & & & \\ & a^i_{20,k} & & & P^i_{20,k})(1-a^i_{20,k}) & & (1-P^i_{20,k})(1-a^i_{20,k}) & \\ & & a^i_{21,k} & & & P^i_{21,k})(1-a^i_{21,k}) & (1-P^i_{21,k})(1-a^i_{21,k}) & \\ & & & a^i_{3,k} & & & P^i_{3,k})(1-a^i_{3,k}) & (1-P^i_{3,k})(1-a^i_{3,k}) \\ & & & a^i_{4,k} & & & & 1-a^i_{4,k} \end{bmatrix} \quad (2)$$

The priority of repairs in the optimal investor's strategy is determined by the sequence of $FI^{SC}(a^i_{j,J,k})$ magnitudes, where $a^i_{j,J,k}$ represents the percentage of roads with traffic load class k in condition j to be repaired to condition J in year i, and where SC signifies staged construction. These magnitudes depend only on actual probability of changing the condition and construction prices:

$$FI^{SC}(a^i_{20,11,k}) = \frac{G_{3,1,k}}{G_{2,1,k}} - p^i_{20,k}\left(\frac{G_{3,1,k}}{G_{2,1,k}} - 1\right)$$

$$FI^{SC}(a^i_{21,12,k}) = \frac{G_{3,1,k}}{G_{2,1,k}} - p^i_{21,k}\left(\frac{G_{3,1,k}}{G_{2,1,k}} - 1\right)$$

$$FI^{SC}(a^i_{3,13,k}) = \frac{G_{4,1,k} - G_{2,1,k}}{G_{3,13,k}} - p^i_{3,k}\,\frac{G_{4,1,k} - G_{3,1,k}}{G_{3,13,k}}$$

$$FI^{SC}(a^i_{4,13,k}) = \frac{G_{4,1,k} - G_{4,2,k}}{G_{4,13,k}} \quad (3)$$

where: $G_{jJ,k}$ are construction costs of improvement of 1 km of road in class k from condition j to condition J.

The smaller the probability of staying in actual condition, the higher the position on the priority list for improvement. This position is independent of the amount of resources, and the highway manager must adapt the length of segments to be repaired to the obtained a values. This is the basic difference from the so-called priority assessment models, in which a project with a very high rank may be rejected because the segment was too long.

The priority of repairs in the optimal users' strategy is defined similarly to the optimal investor's strategy. It is determined by the sequence of $FU^{SC}(a^i_{j,J,k})$ magnitudes.

$$FU^{SC}(a^i_{20,11,k}) = Q^i_k \frac{T_{3,k} - T_{1,k} - p^i_{20,k}(T_{3,k} - T_{2,k})}{G_{2,1,k}}$$

$$FU^{SC}(a^i_{21,12,k}) = Q^i_k \frac{T_{3,k} - T_{1,k} - p^i_{21,k}(T_{3,k} - T_{2,k})}{G_{2,1,k}}$$

$$FU^{SC}(a^i_{3,13,k}) = Q^i_k \frac{T_{4,k} - T_{2,k} - p^i_{3,k}(T_{4,k} - T_{3,k})}{G_{3,13,k}}$$

$$FU^{SC}(a^i_{4,13,k}) = Q^i_k \frac{T_{4,k} - T_{2,k}}{G_{4,13,k}} \qquad (4)$$

where

Q^i_k = mean AADT*365 in the ith year on the road in the kth class; and

$T_{j,k}$ = vehicle operating costs per vehicle kilometer for the traffic composition on roads in the kth class and jth condition.

These relations show that the priority of intervention in the optimal users' strategy depends on the traffic volume and the ratio *(operating costs)/(construction costs).* The results for two initial network conditions and for the annual budget of $2,400/km for a two-lane road are presented in Figures 7 to 14.

Figures 7 and 8 show backlog for one-step and staged construction, respectively, whereas Figures 9 and 10 exhibit extra users' costs for the same scenarios. Initially, the network is assumed to be in poor condition. Figures 11–14 are similar to Figures 7–10; the difference is that the assumed initial condition of the network is good. Though the backlog and extra users' costs are almost the same for both types of construction, general network condition differs considerably (Figure 15).

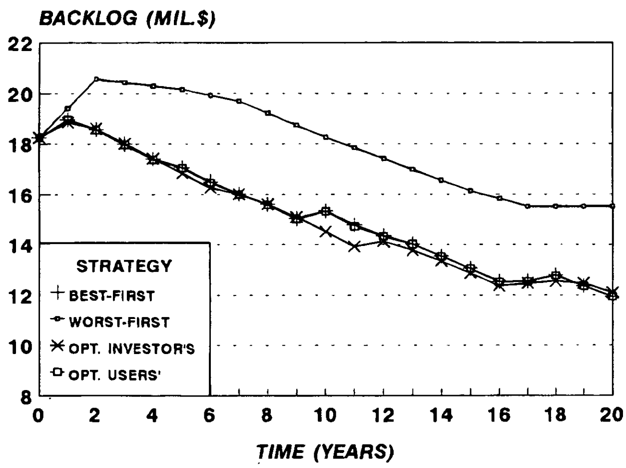

FIGURE 7 Backlog for one-step construction with $2,400/km/year budget and poor initial network condition.

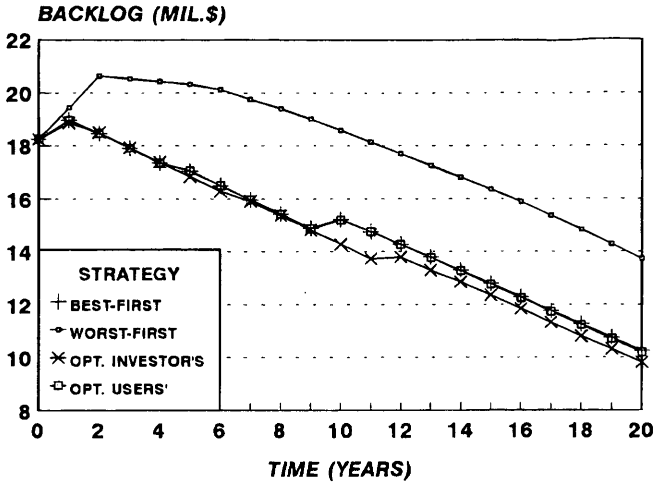

FIGURE 8 Backlog for staged construction with $2,400/km/year budget and poor initial network condition.

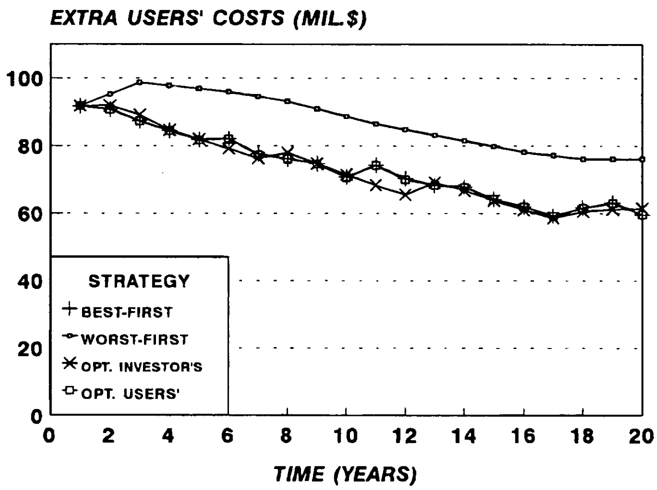

FIGURE 9 Extra users' costs for one-step construction with $2,400/km/year budget and poor initial network condition.

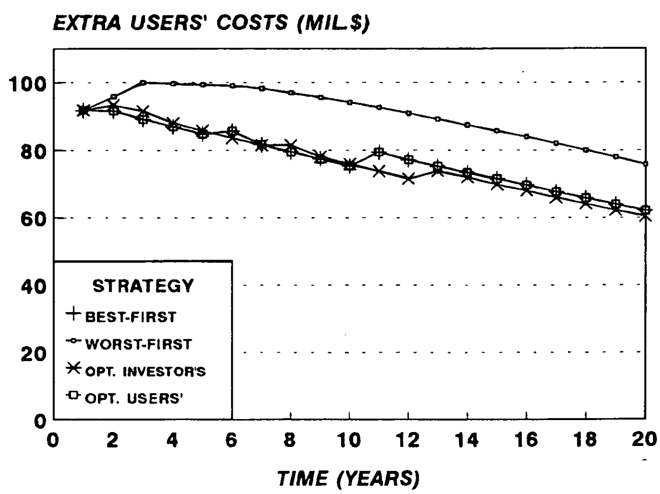

FIGURE 10 Extra users' costs for staged construction with $2,400/km/year budget and poor initial network condition.

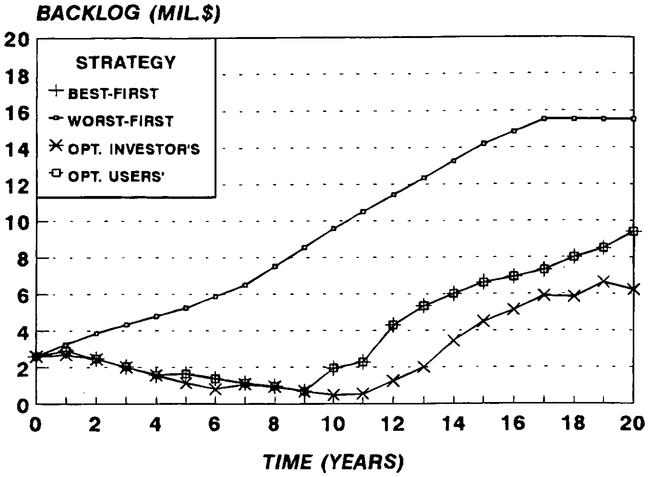

FIGURE 11 Backlog for one-step construction with $2,400/km/year budget and good initial network condition.

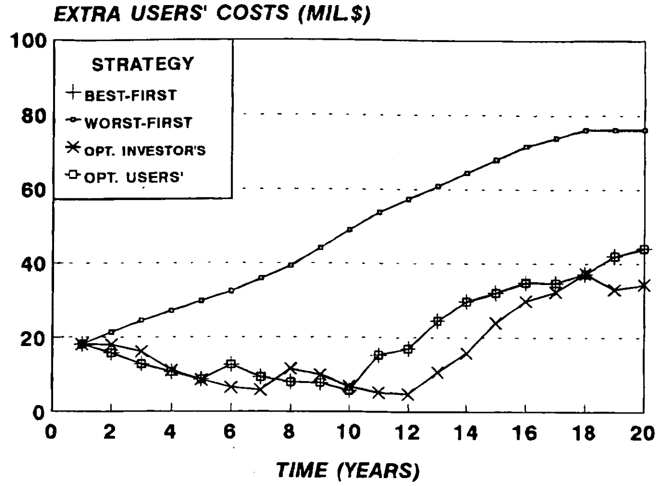

FIGURE 13 Extra users' costs for one-step construction with $2,400/km/year budget and good initial network condition.

FINDINGS AND CONCLUSION

Based on the analysis presented, it could be concluded that in the case of staged construction, the basic relation between worst-first and other strategies, obtained for one-step construction, is not disturbed. Staged construction produces neither exceptional savings nor extra costs during the first 15 years. After that, such construction seems to be even more favorable.

Important effects of pavement improvement may be expected in incidence of fewer accidents. The highest risk is usually recorded on slippery, but not very rough, pavements that belong to the "good" pavement category. So, the greatest benefits in safety may appear as a consequence of surface treatment or even some routine maintenance treatments. This fact supports the best-first strategy but does not influence the relation between one-step and staged construction because it concerns only the layer's lifetime. No appropriate accident data base was available to provide a true picture of these relations. Thus, the entire segment of accident costs has not yet been introduced. Some other facts dealing with long-term thin and thick layer's performance could not be incorporated before a precise calibration. Though more refined data and a more detailed analysis are needed for such investigations, a general conclusion may be drawn from the results: If no great savings in future investments can be expected when applying staged construction, there are good reasons to introduce high standards for capital maintenance immediately.

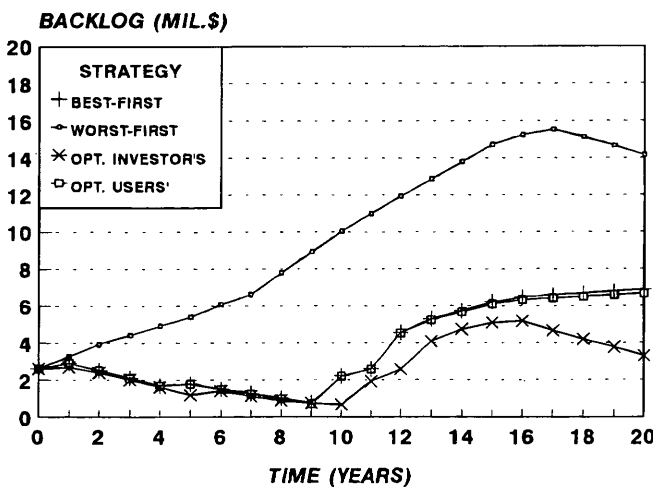

FIGURE 12 Backlog for staged construction with $2,400/km year budget and good initial network condition.

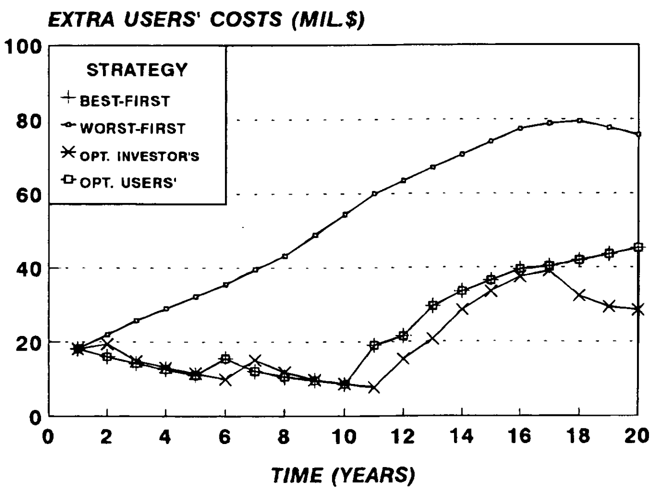

FIGURE 14 Extra users' costs for staged construction with $2,400/km/year budget and good initial network condition.

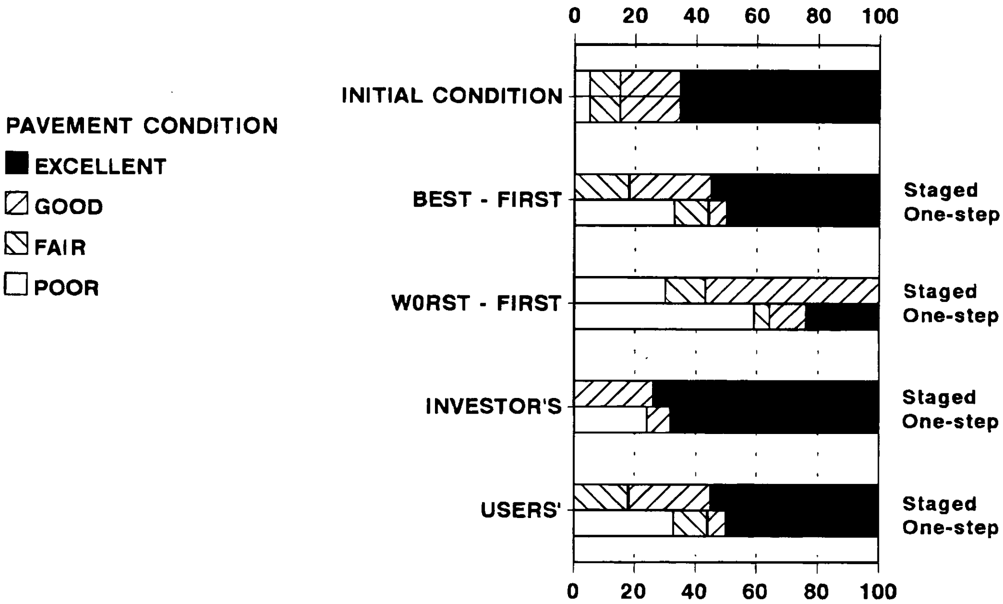

FIGURE 15 Pavement condition after 20 years for $2,400/km/year budget and good initial network condition.

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