Impact of Different Economic Criteria on Priorities in Pavement Management Systems

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The results of a recent study conducted at the Faculty for Traffic and Transport Engineering, University of Belgrade, Belgrade, Yugoslavia, are presented. The study was performed to investigate whether there is any theoretical principle that could be implemented as a guiding rule when defining a capital pavement maintenance strategy. Road network pavement deterioration and repair were described by the controlled nonhomogeneous Markov process. Six guiding rules were defined and a theoretical proof was provided, that is, that the rule "the sections in the worst state have the first priority" could never be the best strategy when considering the effects on a network as a whole when budgets are restricted. The results of a computer program based on these principles are presented.

The basic dilemma of spending a restricted budget during a longer period could be defined as whether

1. To repair a greater extent of the network in 1 year with the measures of a lower standard or
2. To repair a minor extent of the network in 1 year, but achieving at once an excellent state.

The results of many studies have shown that the staged construction could almost never be the best strategy; only a severe budget restriction could impose the achievement of a long service life of pavements in two or three steps. So we considered only Orientation 2 of the maintenance strategy. An additional question was imposed: In what way does the sequence of repair work influence the speed of improving the overall quality of the network? This question is treated in the Pavement Management Forecasting System (PMF) (*1*), which considers only the effects on the quality of the network itself without an analysis of costs to users or of accidents.

One of the most serious obstacles for the implementation of the modern software for pavement management in countries with poor economies is the lack of reliable data. The devices for measuring a bearing capacity and for the calibration of surface deficiencies are expensive. Moreover, it takes years to quantify the parameters describing pavement behavior under local climate conditions and the conditions of the physical environment. This can postpone the introduction of a modern management system in many regions with poor economies.

Homogeneous Markov chains are frequently used to describe pavement deterioration over time on a network as a whole. The probability that a certain section would remain in the same state or pass into a worse state in regions where periods of intensive road construction are followed by periods of almost total absence of investment depends on the moment considered. That is why the homogeneous process is not convenient for the description of the behavior of such a road network.

For these reasons the present study had the following objectives:

- To establish a mathematical model that will present the impact of the amount of the available budget on the network quality as a whole in a simple and as real a way as possible;
- To analyze the effects of strategies defined as principles to obtain instructions, that is, guiding rules, for the definition of the projects in more detailed models;
- To establish criteria that will separately reflect the road manager's and users' interests and quantify their mutual relations under various circumstances;
- To develop a computer program that will contain all the stated theoretical assumptions and enable the use of currently available data, but at the same time allow the use of more precise data to be acquired in the future; and
- To determine the trigger values of the traffic volume for which particular strategies are competent on the basis of such a program.

MATHEMATICAL MODEL

The mathematical model was established in two phases:

- A simple alternative was set up to make clear whether any regular relationship existed between the sequence of repair works and their effects, and
- An alternative closer to practice was also set up.

Starting Assumptions

Because these considerations were primarily of a theoretical character and a very poor data base was available, the mathematical model was based on the following assumptions:

1. The change in the condition of the road network can be described by nonhomogeneous Markov chains. The probability of a change in the condition of a certain road section depends on the relation between the length of the service life and the time spent in operation. Because no systematically collected road network condition data were available, the only reliable data—the year of

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construction, the length of the design period, and the type of intervention during the past period—had to be used.

2. Road network sections were classified into a finite number of states (four) on the basis of an indicator that was decisive (or in correlation with the decisive indicator) for the maintenance treatment. Because the model was based on pavement performance curves, which were also used for design, and served primarily for the choice of principles, not for the choice of the treatment type, only four states were adopted. The pavement states were delimited in such a way that improvement to the excellent state might be obtained by the following interventions:

- From a good to an excellent state: surface treatment and thin overlay without increasing the bearing capacity,
- From a fair to an excellent state: strengthening, and
- From a poor to an excellent state: reconstruction (similar to the PMF model).

3. All road network sections behave according to the same deterioration model provided by a standard design procedure. Although different design methods were applied in the previous period, the performance curve expected by the standard method of pavement design was adopted.

4. Interventions either turn pavement back into an excellent condition or do not influence the pavement such that it changes into any other condition. This means that routine maintenance costs depend on the pavement condition but do not influence the probability of the change of condition. If small repairs are not performed in time, pavement deterioration is accelerated, but no reliable quantification could be done with the available data. If appropriate information on those relations were available, that information could be entered into the program by adapting the input data.

Description of Road Deterioration and Repair

The entire road network condition can be described by the state vector of the network:

$$\alpha_k^i = (\alpha_{1k}^i, \alpha_{2k}^i, \alpha_{3k}^i, \alpha_{4k}^i) \qquad \sum_{j,k} \alpha_{j,k}^i = 1 \tag{1}$$

where α_{jk}^i presents the participation of sections in j state of roads in class k in the ith year on the entire road network, where j is 1 for excellent condition, j is 2 for good condition, j is 3 for fair condition, and j is 4 for poor condition (Figure 1).

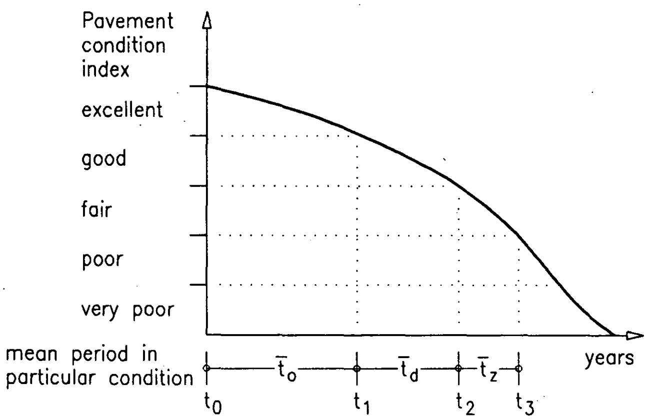

FIGURE 1 Average time of pavement service in particular condition.

The classes of roads present the road network classification according to traffic volume categories expressed by the average annual daily traffic (AADT). The limits among individual classes have been determined on the basis of a traffic survey, so that each class (k = 1, 2, 3, 4) covers a typical traffic composition (Figure 2) in the following way (where vpd is vehicles per day):

AADT1:		AADT	>10,000 vpd
AADT2:	10,000>	AADT	> 5,000 vpd
AADT3:	5,000>	AADT	> 2,000 vpd
AADT4:	2,000>	AADT	

If p_{jk}^i presents the probability that the road network section in class k of traffic volume in the year i will remain in the state j and $1 - p_{jk}^i$ is the probability that it will pass into a worse state, then the transition matrix for the network without interventions (except routine maintenance) will look like

$$P_{ik} = \begin{vmatrix} p_{1k}^i & 1-p_{1k}^i & 0 & 0 \\ 0 & p_{2k}^i & 1-p_{2k}^i & 0 \\ 0 & 0 & p_{3k}^i & 1-p_{3k}^i \\ 0 & 0 & 0 & 1 \end{vmatrix}$$

where p_{1k}^i, p_{2k}^i, and p_{3k}^i are natural conditions, that is, the consequence of the general state of pavement on the part of network in the kth class. Because interventions on the network either change it into an excellent condition or do not influence its condition at all, the transition matrix for the network expected to be improved will be

$$P_{ik} = \begin{vmatrix} p_{1k}^i & 1-p_{1k}^i & 0 & 0 \\ a_{2k}^i & p_{2k}^i \cdot (1-a_{2k}^i) & (1-p_{2k}^i)\cdot(1-a_{2k}^i) & 0 \\ a_{3k}^i & 0 & p_{3k}^i \cdot (1-a_{3k}^i) & (1-p_{3k}^i)\cdot(1-a_{3k}^i) \\ a_{4k}^i & 0 & 0 & 1-a_{4k}^i \end{vmatrix}$$

where

a_{2k}^i = participation of network length of the kth class in good condition improved at the ith step (year) to excellent condition by surface treatment or overlay $d \leq 4$ cm,

a_{3k}^i = participation of network length of the kth class in fair condition improved at the ith step to excellent condition by strengthening, and

a_{4k}^i = participation of network length of the kth class in poor condition improved at the ith step to excellent condition by reconstruction.

The elements a_{jk}^i must be determined by the optimization process in the context of the available budget.

If the average time that the pavement remains in excellent condition is t_o years, and if t_d and t_z are periods for good and fair condition, respectively, then

$$p_{jk}^i = \frac{\sum_{l=t_{j-1}}^{t_j - 1} s_{lk}^i}{\sum_{l=t_{j-1}}^{t_j} s_{lk}^i} \tag{2}$$

where s_{lk}^i is the participation of road network length of class k being in operation l years considered in ith year.

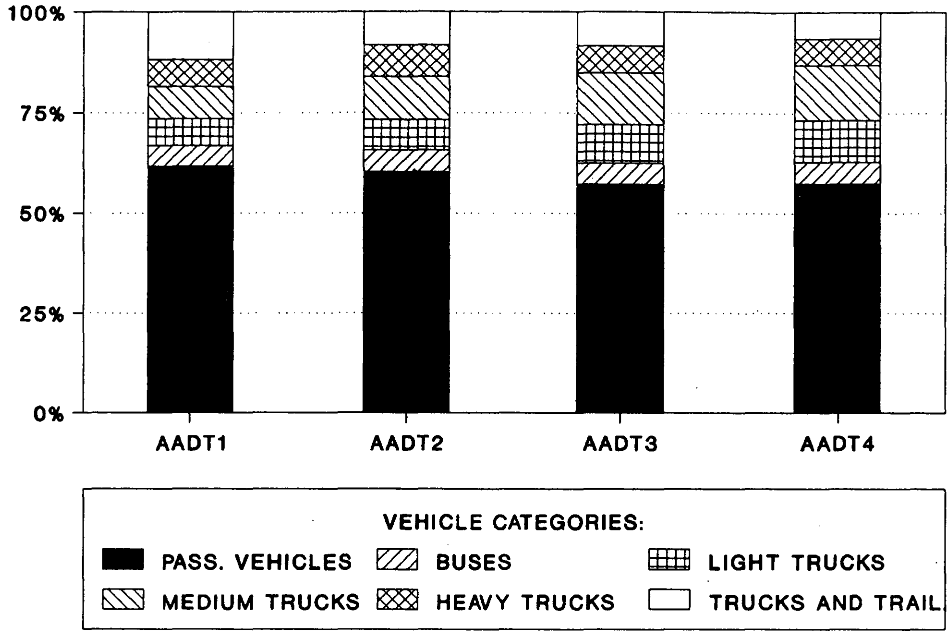

FIGURE 2 Traffic composition depending on traffic volume.

Definitions of Objectives and Criteria

The basic aim is a high-quality network. That means that

α_{1k} is >1.0 and α_{2k}, α_{3k}, and α_{4k} are >0.

The criterion of a network quality from the investor's point of view is the total sum B^i of funds needed to bring the whole network into an excellent condition (backlog) in the ith year.

$$B^i = \sum_{j,k} \alpha^i_{jk} \cdot G_{jk} \cdot L_k \tag{3}$$

where

G_{jk} = the average repair cost to bring 1 km of pavement in class k and in state j into excellent condition,
L_k = the length of roads in class k of the network considered, and
i = current year of the period considered.

The highest network quality is obtained when B^i is equal to 0. The best strategy is the one that reduces B^i to the minimum in the quickest way, with the assumption that the total network length does not change significantly during the period considered. The adopted sum B^i

- Most clearly reflects the effects of the repair strategy on the quality of the network from the investor's point of view,
- Contains the comparative rating of particular road conditions through unit repair costs,
- Uses data in a form typical for the proposed mathematical model, and
- Can be adapted to different evaluation systems.

The primary criterion from the users' point of view is minimal vehicle operating costs. For the whole network considered these costs are

$$S^i = 364 \cdot \sum_{j,k} \overline{\text{AADT}^i_k} \cdot \alpha^i_{jk} \cdot T_{jk} \cdot L_k \tag{4}$$

where

S^i = total users' costs on the whole network in the ith year of the period considered;
T_{jk} = users' costs per vehicle kilometer pondered for average traffic composition in class k of traffic volume ($k = 1, 2, \ldots, m$) on pavement in condition j, where T_{1k} is T_{min} on pavement in excellent condition; and
AADT^i_k = average annual daily traffic on roads of class k in the ith year.

The users' costs were calculated by means of the vehicle operating cost (VOC) (*2*) model, which is a part of the HDM-III program, so that results could be compared with the results of similar methods. The data and standards on vehicles and pavements taken from related studies were used without any statistical verification of their reliability. The quantification and validation of parameters will be done in the final phase, after examining the model behavior under hypothetical conditions. To make the data manipulation easier, the following expression was mostly used:

$$\Delta S^i = 364 \sum_{j,k} \overline{\text{AADT}^i_k} \cdot (T_{jk} - T_{1k}) \cdot \alpha^i_{jk} \cdot L_k \tag{5}$$

which represents the additional users' costs because of the imperfect state of the pavement, that is,

$$S^i = 364 \sum_{jk} \overline{\text{AADT}^i_k} \cdot T_{1k} \cdot L_k + \Delta S^i$$

Accident costs have not been included up to now since the available evidence could not be rapidly adapted to the needs of this model, but a modification of the model could easily be done.

The routine maintenance costs r_k^i are a very important measure of the effects of particular strategies. They are several times smaller than backlog or users' costs, but they have the same structure.

$$r_k^i = L_k \cdot \sum_j \alpha_{jk}^i \cdot r_{jk} \qquad (6)$$

where r_{jk} is an average cost of routine maintenance for 1 km of road in class k and in state j. Only additional routine maintenance costs because of an imperfect state of the pavement are a part of the total effects presented here.

Definitions of Strategies

Strategies were defined as guiding rules concerning priorities. The program searched for the best sequence of repairs in each step, that is, year. Because the analysis of effects should give also an answer to the question: Does a consistent application of a certain basic rule (Strategies I to IV) give better results than the sequence of interventions obtained by optimization at each step? the following strategies were defined.

Strategy I (the best first). Resources are spent primarily to repair roads in better condition, and the rest is spent on roads in worse condition.

Strategy II (proportional). Resources are spent in proportion to the length of roads in particular condition categories.

Strategy III (combined). Resources are spent on the part of network whose state is below the minimal standards, and the rest is spent according to Strategy I.

Strategy IV (the worst first). Resources are spent primarily on repairs for the worst sections, and the rest is spent on sections in a better state.

Strategy V (investor's point of view). Resources are spent according to the sequence determined by optimization at every step (year), with the maximal benefit in network quality (backlog) as the primary criterion.

Strategy VI (users' point of view). Resources are spent according to the sequence determined by optimization at every step, applying minimal users' costs as the primary criterion.

FINDINGS

Optimal Sequence of Repair Works

The state of the network before the implementation of particular strategies was described by α_{k0}. The transition matrix of the road network condition in the ith year for the class of roads k was defined by P_{ki}, so the road network state vector after n years of application of some strategy would be

$$\alpha_k^n = \alpha_k^{n-1} \cdot P_{nk} = \alpha_k^0 \cdot P_{1k} \cdot \ldots \cdot P_{ik} \cdot \ldots \cdot P_{nk}$$

For each step the elements a_{jk}^i were calculated from the available budget b_g^i in the ith year

$$b_g^i = \sum_{j,k} a_{jk}^i \cdot \alpha_{jk}^i \cdot G_{jk} \cdot L_k \qquad (7)$$

according to the strategy considered. Strategies I to IV have a fixed sequence of work; only the effects backlog B^i, users' costs S^i, and routine maintenance costs were calculated. When the optimization had been performed (Strategies V and VI) the model searched for the sequence of work with minimal backlog or minimal users' costs at every step (year). The optimal sequence was obtained in the following way:

1. *Backlog as an optimization criterion*: The trigger value for the choice of a strategy was found to be

$$r = F(\max a_2) \,/\, F(\max a_3)$$

For $r > 1$ the sequence of repairs is A for good, B for fair, and C for poor roads. For $r < 1$ the sequence of repairs is A for fair, B for good, and C for poor roads.

where

$$F(\max a_2) = (G_{3k}/G_{2k}) - P_{2k}^i\,[(G_{3k}/G_{2k}) - 1]$$
$$F(\max a_3) = (G_{4k}/G_{3k}) - P_{3k}^i\,[(G_{4k}/G_{3k}) - 1]$$
$$F(\max a_4) = 1$$

$G_{j,k}$ = construction costs of bringing 1 km of road in the jth state and the kth category of traffic volume to excellent condition, and

$P_{j,k}^i$ = the probability for a road section to remain in state j in year i.

The fact that

$$F(\max a_2),\ F(\max a_3) > 1, \text{ and } F(\max a_4) = 1$$

means that roads in poor condition must be repaired only if the other two categories have been accomplished. This is the mathematical proof of a logical conclusion that the basic task must be oriented toward stopping the deterioration of better pavements, regardless of whether the available budget is low or high.

2. *The users' costs as an optimization criterion:* The sequence of repairs was determined by the sequence of magnitude of F', so that the sections in a state for which $F'(\max a_j)$ was the greatest had the first priority.

$$F'(\max a_2) = \frac{Q_k^i}{G_{2k}}(T_{4k} - T_{1k})\left(\frac{T_{3k} - T_{1k}}{T_{4k} - T_{1k}} - p_{2k}^i\,\frac{T_{3k} - T_{2k}}{T_{4k} - T_{1k}}\right)$$

$$F'(\max a_3) = \frac{Q_k^i}{G_{3k}}(T_{4k} - T_{1k})\left(1 - p_{3k}^i\,\frac{T_{4k} - T_{1k}}{T_{4k} - T_{1k}}\right)$$

$$F'(\max a_4) = \frac{Q_k^i}{G_{4k}}(T_{4k} - T_{1k})$$

where Q_k^i is (mean AADT $\cdot$ 365) in year i on the roads of the kth class, and, $T_{j,k}$ is VOC per vehicle kilometer for the traffic composition on roads in class k and in state j. These relations show that the road section in any condition could have the first priority, mostly depending on the traffic volume and the ratio of operating costs/construction costs.

Data Used

It was extremely difficult and tiresome to find consistent and reliable data on capital and routine maintenance from our practice. Different data or default values were taken from the available studies and programs with minimal corrections. Thus, the effects presented here can provide only an idea of the relations. For practical use the whole input had to be reconsidered. The sources of data used in this study were as follows:

1. The mean time of service for pavements in particular conditions and the construction costs were adopted from PMF.
2. Maximal possible value for roughness was adopted from HDM-III to make the vehicle operating costs on poor roads as great as possible.
3. The prices for VOC input were average prices in Belgrade in October 1992.
4. Data for three sets of representative vehicles were used in this model. The two sets were suggested by two independent groups of experts (without any statistical background), and one was taken from HDM-III. The differences were evident, but not so important that the strategy had to be changed.
5. Routine maintenance costs were adapted from different sources.
6. The road network in extremely bad condition (Figure 3) was adopted in the example presented to show the logic of the model.

Although data from different sources were aggregated the results were very stable. Little changes could not influence the choice of strategy. Some of the results are presented in the following.

Results

We expected that the best-first strategy would always be the best one from the investor's point of view and that the worst-first would be the best strategy from the users' point of view only on the roads with high traffic volume. For this reason we searched for such a set of data that would give the opposite strategies from two viewpoints. A very high traffic volume was adopted for two-lane roads to obtain the following results. The consequent application of the best-first and worst-first strategies was also considered to see which sequence prevailed in an optimal choice and to see whether the optimization would yield significantly better results than those from the fixed sequence.

Contrary to expectations, the worst-first strategy was never optimal in the frame of the input data. Although there were only minor differences between the effects obtained by the three good strategies, the participation of road length under particular conditions after a 10-year period was quite distinct (Figure 3). These distinctions might influence the final decision only through routine maintenance costs. The magnitude of these costs (Figure 4), users' costs (Figure 5), and backlog (Figure 6) were not of the same level.

The benefits in relation to the do-nothing alternative were usually considered in the evaluation procedures. This relation is shown in Figure 7. The difference between do nothing and the worst-first strategy was almost the same as those between the worst-first and the three good strategies. Such a promising picture was changed after the number of thin layers had been limited.

The PMF model gave the same advantage to the "best-first" strategy, but in that model only backlog existed as a criterion. The choice of strategy from the users' viewpoint depended on the differences $T_{j,k} - T_{j-1,k}$ of users' costs. A large increase in these dif-

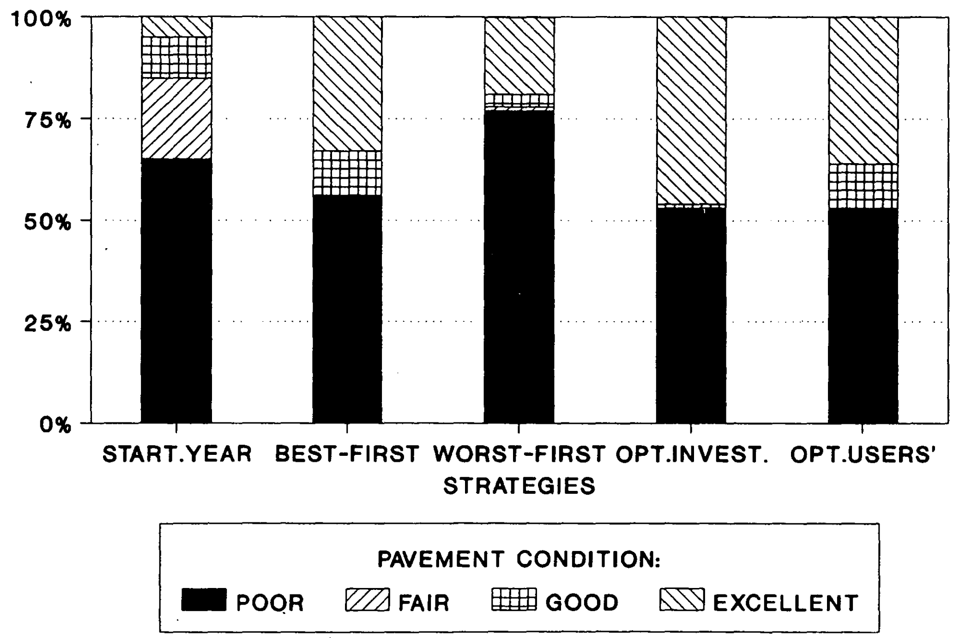

FIGURE 3 Pavement condition before and after 10-year application strategies.

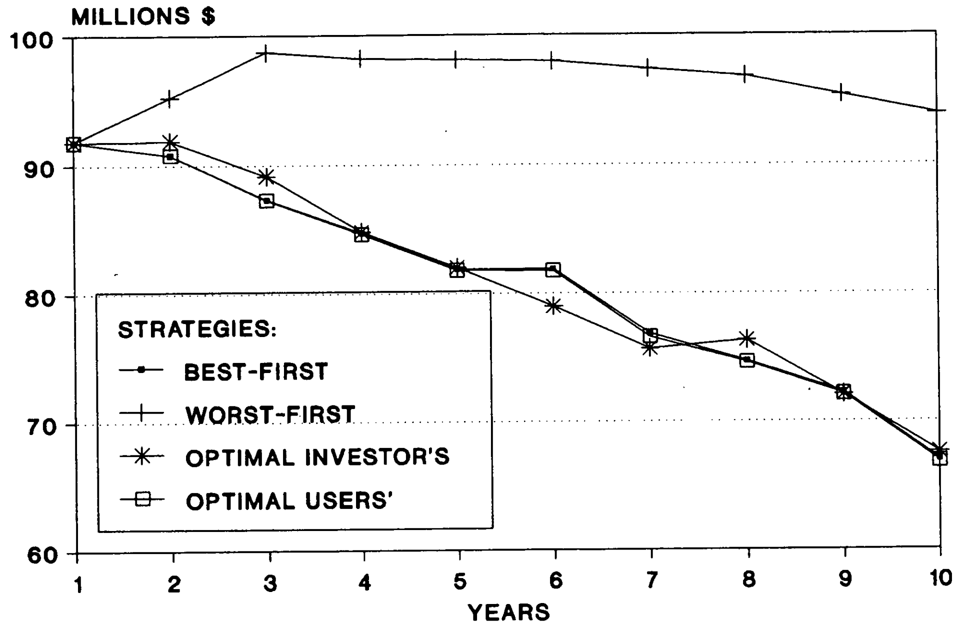

FIGURE 4 Additional users' maintenance costs.

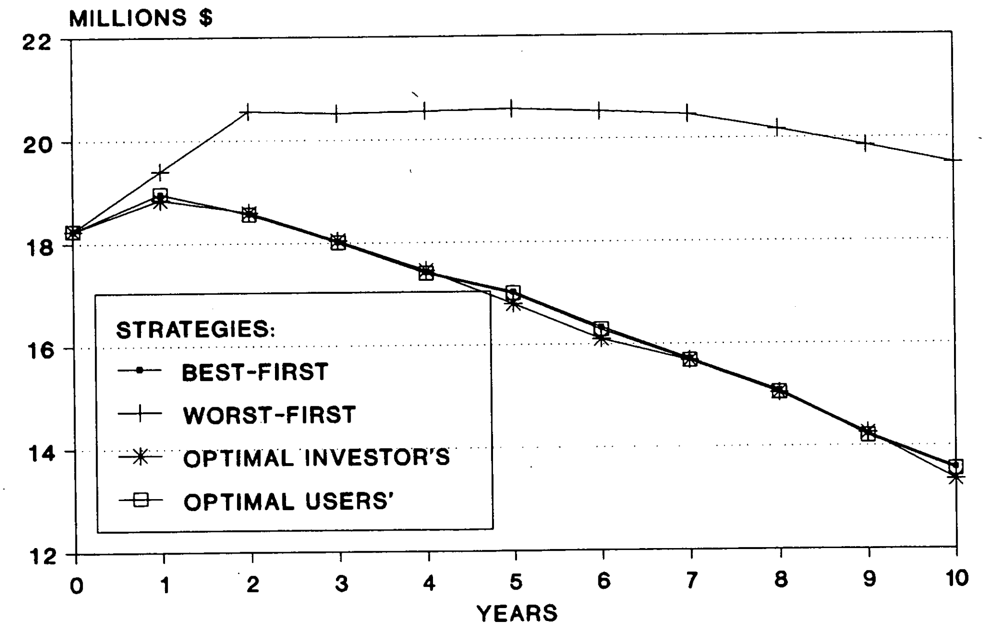

FIGURE 5 Additional users' costs because of pavement deficiencies (ADDT = 12,000 vpd; L = 250 km).

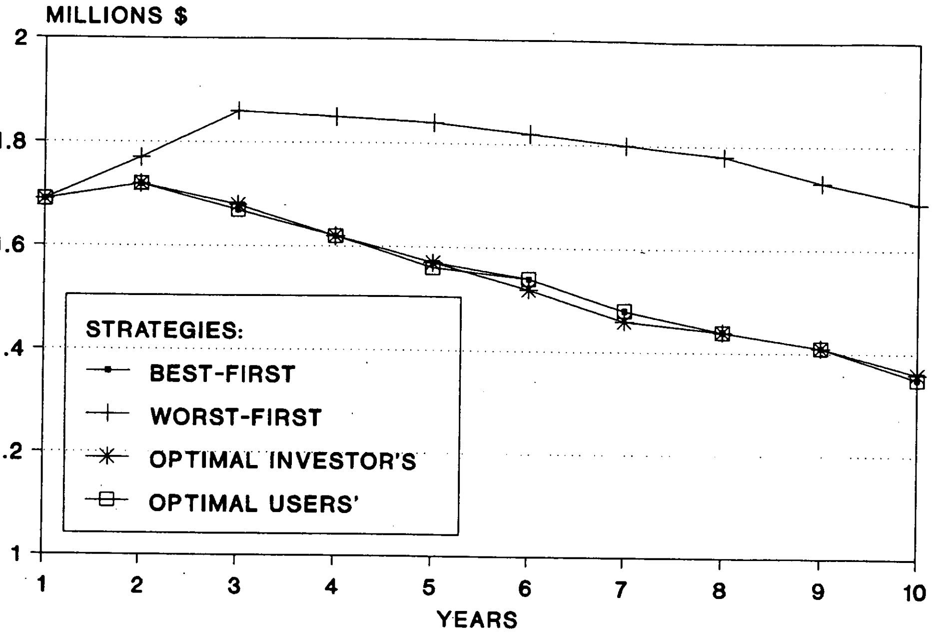

FIGURE 6 Backlog funds needed to bring entire network to excellent state in 1 year (ADDT = 12,000 vpd; L = 250 km).

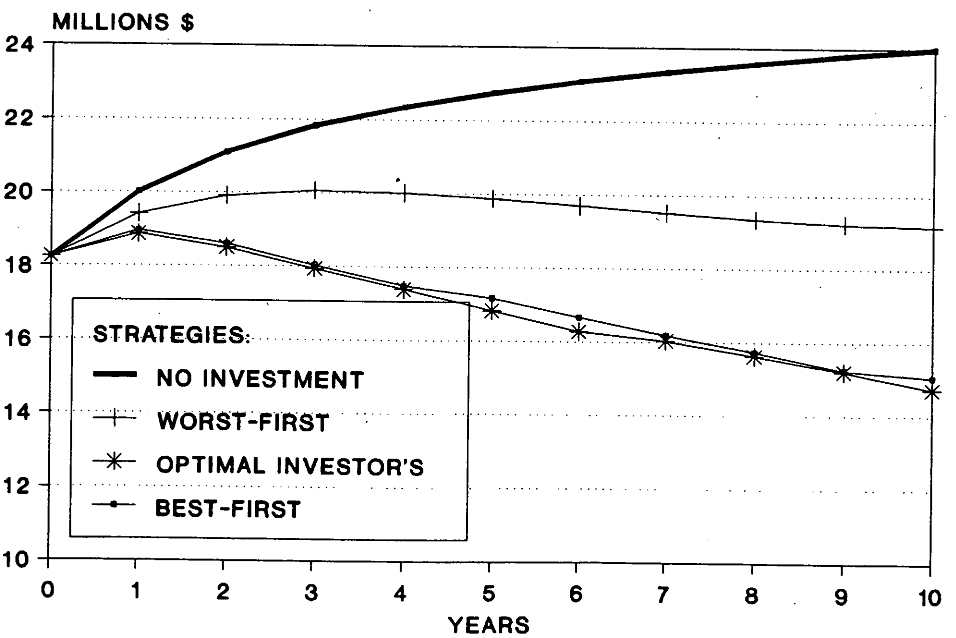

FIGURE 7 Backlog for network with and without investment.

ferences had to be made to change the decision. A detailed investigation of the upper and lower limits of prices in a stable economy is still needed to define more exactly the frames in which particular strategies are competent.

The function of pavement behavior represented here by means of service life in particular states had a great impact on the results. An analysis of these relations under different circumstances is still needed.

In spite of the expected changes in the results in case of some other physical and economic environment, the following conclusions can be drawn:

1. Backlog or some familiar criterion must find its place in the maintenance strategy evaluation for all classes of roads, and
2. Effects of any greater improvement must be observed only on a network as a whole.

INTRODUCTION OF LIMITATION IMPOSED BY PRACTICE

The next step to the real-world situation was the introduction of the principle that after the application two thin layers, that is, after two improvements from a good to an excellent state, the road section must be strengthened. This was performed by introducing several more classes of pavement condition categories, which enabled the network structure to be visible at every step.

The transition matrix had the following shape:

$$\begin{vmatrix} p^i_{10,k} & & & 1-p^i_{10,k} & & & \\ & p^i_{11,k} & & & 1-p^i_{11,k} & & \\ & & p^i_{12,k} & & & 1-p^i_{12,k} & \\ & a^i_{20,k} & & p^i_{20,k}\cdot(1-a^i_{20,k}) & & (1-p^i_{20,k})\cdot(1-a^i_{20,k}) & \\ & & a^i_{21,k} & & p^i_{21,k}\cdot(1-a^i_{21,k}) & (1-p^i_{21,k})\cdot(1-a^i_{21,k}) & \\ a^i_{3,k} & & & & & p_{i3,k}\cdot(1-a^i_{3,k}) & (1-p^i_{3,k})\cdot(1-a^i_{3,k}) \\ a^i_{4,k} & & & & & & 1-a^i_{4,k} \end{vmatrix}$$

The vector of the network state is

$$\alpha^i_k = (\alpha^i_{10,k}, \alpha^i_{11,k}, \alpha^i_{12,k}, \alpha^i_{20,k}, \alpha^i_{21,k}, \alpha^i_{3,k}, \alpha^i_{4,k})$$

where, for the part of network in the kth class of traffic volume in a year i

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

To observe the consequences of the introduction of such a matrix the same data were processed in the basic model and in the improved model. For that reason we had to adopt a longer design period to make up the changes. In practice, the starting state vector would reflect the interventions done in the previous period. The results are presented in Table 1 and Figures 8 and 9.

The results are logical and expected. The only surprise is the stationary state in some strategies (Figure 8, years 17 to 20). It means that the process becomes homogeneous after several years. In that case no increase in quality can be expected without an increase in budget resources. It also means that a stable investment in a very poor network leads to a homogeneous process and that conditions for such a development could be defined. The most important is that the worst strategy achieves homogeneity the first.

CONCLUSIONS AND FINAL REMARKS

No significant deviations from the results obtained in the basic alternative (Table 1) were found in the improved alternative of the model. Thus, the worst-first strategy had to be rejected under the circumstances considered in the paper. We also underline two facts.

1. Investor's and users' criteria produced the effects whose functions had the same shape.

TABLE 1 Effects of Particular Strategies in Basic and Improved Simulation Model

STRATEGY	YEAR	BACKLOG (thousands $)	ADDITIONAL USER'S COSTS (thousands $)	ADDITIONAL ROUTINE MAINT.COSTS (thousands $)
Effects of good strategies without limitation for thin layers				
BEST-FIRST	20	10589	51611	957
INVESTOR'S	20	10389	51317	936
USER'S	20	10574	51536	956
Effects of good strategies with the limitation imposed				
BEST-FIRST	16	12542	61957	1130
	17	12557	59225	1141
	18	12793	61551	1169
	19	12360	63141	1121
	20	11933	59550	1076
INVESTOR'S	16	12372	61043	1115
	17	12475	58615	1139
	18	12564	60551	1149
	19	12473	61122	1134
	20	12096	61433	1092
USER'S	16	12525	61876	1129
	17	12542	59144	1141
	18	12775	61485	1168
	19	12354	62976	1120
	20	11927	59610	1076

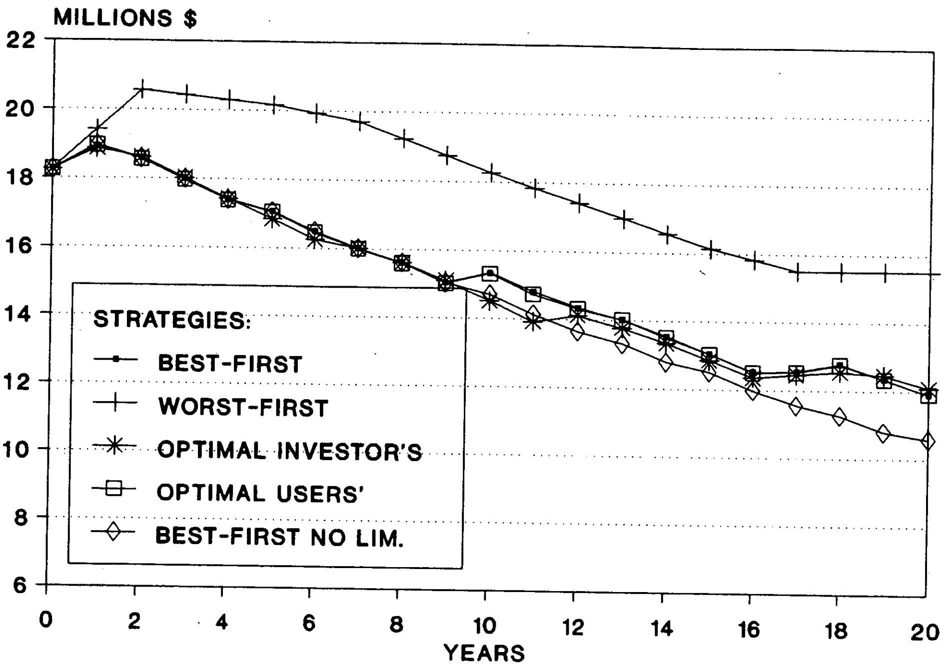

FIGURE 8 Backlog for different strategies with and without limitations of maximum of two thin layers.

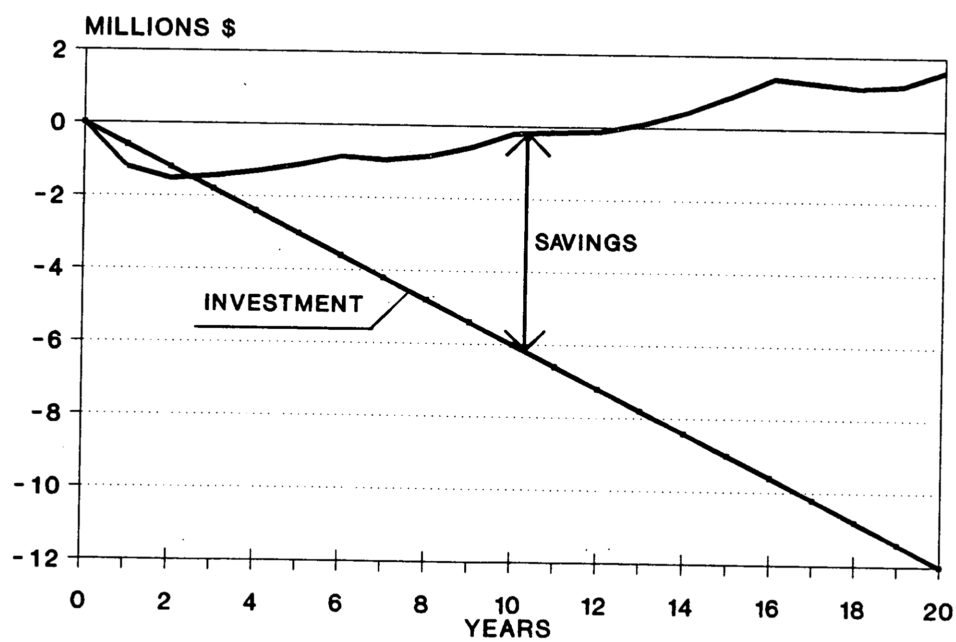

FIGURE 9 Savings (backlog plus routine maintenance) versus investment.

2. Differences between the effects of particular good strategies were under the level of accuracy of the input of this model.

Actually, the consequences of the limitation were reflected in greater oscillations of the effects. For this reason the backlog of the optimal investor's strategy in the 20th year was greater than the backlog of the users' strategy. Cumulative savings could help the final decision, but no further economic analysis has been performed (like internal rate of return or net present value). Such an analysis would be needed for the opposed strategies or when the accuracy of the parameters in the model and the input data had been checked.

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