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# Systems Approach to Flexible Pavement Design and Management



*An NCHRP staff digest of the essential findings from the final report on NCHRP Project 1-10A, "Systems Approach to Pavement Design - Implementation Phase," by R. C. Lytton and W. F. McFarland, Texas Transportation Institute, College Station, Texas.*

## THE PROBLEM AND ITS SOLUTION

One of the first activities of the Highway Research Board (formed more than 50 years ago and recently renamed the Transportation Research Board to reflect its actual scope of operation) was to investigate the economics of highway improvements. At its Fourth Annual Meeting, in December 1924, the Committee on Economic Theory of Highway Improvements reported that the superiority of aggregate-surfaced roads over ordinary earth roads was generally conceded, but highway officials were plagued with the question of whether aggregate surfacing was a good investment from a financial standpoint. A study conducted at that time determined that, on the basis of the cost of the road itself, including such items as interest on investment and maintenance, and the cost of operation of the vehicles using the road, a good aggregate-surfaced road was less costly in terms of total annual cost of transportation per mile than either an earth-surfaced or a paved road when traffic averaged 100 vehicles per day. After this early interest in the economics of highway improvements, emphasis shifted to the structural design of pavements to withstand the effects of traffic and environmental conditions.

In recent years, there has been renewed interest within the highway field in the concept of total cost analysis. Acceptance of the systems approach to the design and management of pavements is a most timely development because new legislative funding likely will apply to all modes of transportation. Therefore, determination of the total cost of movement of people, goods, and services will be necessary to determine priorities for use of funds and material resources. A Systems Analysis Model for Pavements (SAMP5), as described in *NCHRP Report 139*

"Flexible Pavement Design and Management - Systems Formulation," is one approach to considering initial construction, operational, and user costs in the decision-making process. The objectives of Project 1-10A were to finalize SAMP5 as an operational computer program, including preparation of a user's guide, and to pilot test the program in several states. The project was successful in that SAMP5 has been improved to SAMP6, an operational computer program that provides a basis for selecting flexible pavement design and management strategies with the lowest predicted total cost over a prescribed analysis period when considering such cost elements as initial construction, routine maintenance, periodic rehabilitation, interest on investment, salvage value, and roadway user costs. The SAMP6 program uses the AASHTO Interim Guides as its structural subsystem and the predicted decrease in serviceability with time and traffic as developed at the AASHO Road Test. Loan copies are available on magnetic tape from the Program Director, NCHRP, Transportation Research Board, 2101 Constitution Ave., N.W., Washington, DC 20418. Implementation of the program will require a policy decision to use the systems approach to pavement design and management, the availability of suitable computer facilities and personnel, and a certain amount of modification of the current system to reflect the unique facets of an individual agency's approach to pavement design.

## FINDINGS

A schematic diagram of the systems approach to pavement design and management is shown in Figure 1. SAMP6 is capable of considering all aspects of the process as shown except those of the cost of seal coats and the cost of skidding accidents. Although SAMP6 is the best operational model available at the present time, continued modification should add the missing subsystems and improve others, particularly with regard to user costs, maintenance costs, and prediction of structural performance.

The SAMP6 program requires 12 classes of input variables. A general description of each follows.

Program Control and Miscellaneous Variables. Although listed as miscellaneous, some of these variables are among the most important in the entire program. They include the length of the analysis period in years, the number of lanes of a highway in both directions, the width of each traffic lane, and the interest rate or the time value of money.

Environmental and Serviceability Variables. Two types of environmental variables are considered. One is the regional factor that accounts for general climatic and geologic effects of the region. The second environmental variable is that for expansive clay. For expansive clay, three input variables are required: one gives the frequency of occurrence of expected expansive clay trouble spots, a second indicates how active the soil is, and the third gives the rate at which expansive clay roughness develops. Because of the similarity in the roughness patterns and growth characteristics of expansive clay to those of frost heave, it is expected that this same model can be modified to account for frost effects.

Three serviceability variables include the serviceability index of the pavement immediately after construction, the serviceability index of the pavement immediately after an overlay, and the minimum acceptable serviceability index at which an overlay should be placed.

Traffic and Reliability Variables. Average daily traffic figures at the beginning as well as the end of an analysis period are input variables. At present, traffic is assumed to increase uniformly from the beginning to the end of the analysis period, but this can be modified to suit changing needs. Traffic input is converted to an estimate of the equivalent 18-kip, single-axle loads that are expected to be applied to the pavement within an analysis period.

Two reliability variables include a coefficient of variation and a confidence level indicator. A designer is required to furnish various stiffness coefficients, soil support values, and a regional factor, all of which must be estimated on the basis of field experience and some laboratory tests. Each designer having some experience using the design method contained within the AASHTO Interim Design Guide has some knowledge of the range of accuracy for each of these variables. The coefficient of variation is that percent of the average into which 70 percent of all values observed will fall. The confidence level indicator is the certainty of the designer that the pavement will endure for at least a minimum period of time before it requires the first overlay and subsequent overlays. The confidence levels that can be selected within the program vary between 50 percent and 99.9 percent.

Constraint Variables. Constraint variables usually are specified either by geometry or by fiscal and management policy. These variables include the minimum time allowed between initial construction and the first overlay and the minimum time allowed between overlays as well. Other important constraints specified are the maximum funds available for initial construction, the maximum thickness of initial construction, and the maximum allowable thickness for all combined overlays. The last constraint becomes important where drainage inlets might be covered up by successive overlays or where clearance beneath bridges and other overhead structures becomes critical.

Traffic Delay Variables. These variables affect the cost to the motorist of having to slow down and detour or be diverted around overlay operations. Traffic delay costs usually are not large except in those situations where traffic volume is high. In those cases, delay costs sometimes are of sufficient size to justify the construction of very strong pavements. Variables include the distance traffic is slowed in both the overlay and nonoverlay directions; the detour distance around the overlay zone; the number of hours per day of overlay construction; the number of lanes open in both the overlay and nonoverlay directions; the average approach speed; the average speed of traffic through the overlay zone in both the overlay and nonoverlay directions; and an estimate of the amount of time required for completion of the overlay construction.

Maintenance Variables. Routine maintenance costs are assumed to include all future pavement costs except those associated with overlays. SAMP6 has two different programs for computing routine maintenance costs. One assumes that maintenance costs increase linearly with time after initial construction or overlay. The second routine maintenance costs model is based on *NCHRP Report 42*, "Interstate Highway Maintenance Requirements and Unit Maintenance Expenditure Index." The second model also assumes that maintenance costs vary with time, but it includes other variables such as the number of days per year below freezing temperature, the composite labor rate, the composite equipment rental rate, and a relative material cost for a particular locality and the type of road concerned.

Cross-Section, Cost Model, Shoulder Variables. The optimum pavement design and management strategy depends on the total cost of all materials used in the entire cross section of a pavement, including those materials in the shoulders. Studies with the SAMP6 pavement design system have indicated that the cost of shoulder materials can significantly affect the optimum strategy. The cross-section variables include the width and depth of layers beneath the pavement and shoulders and the total area of fill material outside of these layers. Two cost models can be selected for use in the SAMP6 program. One assumes that costs decrease linearly with increasing layer thickness and the other assumes a logarithmic decrease. Each of these has been found to accurately represent normal variations of costs with layer thicknesses.

Tack Coat, Prime Coat, Bituminous Material Variables. Pavement designers who are interested in using SAMP6 as a cost-estimating tool will find these variables helpful. The costs of tack coat, prime coat, and bitumen and layer thickness at which tack coats will be applied are specified.

Wearing Surface Variables. In some flexible pavements the wearing surface differs from the courses that lie below it in gradation, material coefficient, and costs. It may be a very thin layer used to provide a smooth, quiet ride or high skid resistance. Provision has been made in the SAMP6 computer program for considering separately the wearing surface's structural characteristics, cost, salvage value, density, and asphalt content.

Overlay Variables. When an overlay is applied, the SAMP6 computer program assumes that it covers the full width of the pavement. In addition, if the original pavement shoulders are paved, the overlay material and level-up are assumed to be applied across the shoulder. If the original pavement has shoulders that are not paved, the overlay materials are used only on the traffic lanes and the shoulders are overlaid with the same material used in the top shoulder layer in the original pavement. Provisions are made to specify the minimum and maximum thicknesses of each overlay and the in-place costs of the overlay at those thicknesses.

Pavement Material Variables. All of the materials, including aggregate base and subgrade courses and treated layers which the pavement designer considers to be available for construction, are listed for consideration by the SAMP6 computer program. The designer specifies the maximum and minimum thicknesses and the costs of those thicknesses, as well as the material coefficients for each layer, the location and number of layers in which the material is expected to be used, and the salvage value at the end of the analysis period.

Shoulder Layer Material Variables. Various studies utilizing the SAMP6 computer program indicate that the material used in shoulders, the unit costs, the shoulder slopes, and the way the shoulders are built can affect the choice of an optimum strategy. For this reason the SAMP6 computer program makes provision for including the cost of shoulder material in the complete pavement cross section. Provision has been made in the computer program to use the same materials in the shoulder as those used in corresponding layers beneath the pavement.

Because of the variety of materials and thicknesses available, the SAMP6 program operation normally considers between 1,000 and 2,000 different trial designs. The material properties, traffic, and environmental factors are combined in order to predict a time at which the serviceability index of the pavement will reach the minimum acceptable level. Then for each trial design there are a number of different overlay strategies that could be used. SAMP6 tries all of those which are specified by the designer. To the initial cost and best overlay strategy are added the costs of routine maintenance and user costs, which gives an estimated lowest total cost per square yard of pavement.

The output of the SAMP6 program is provided in three parts, as follows:

1. A summary of the input data.
2. A summary of the best design strategy for each material and layer combination.
3. A summary of the 30 best design strategies in order of increasing total cost per square yard of traffic lane.

The first summary is an echo printing of all of the input data, which designers find useful in checking whether the data are stated as intended. The second part of the output presents a summary of the best design strategies for each set of materials and layers, including the optimum thickness, overlay policy, costs, and other characteristics. Many of these designs may not appear in the over-all summary, which is the third item of output. By comparing these designs with the over-all optimum designs, the program user can determine why some sets of materials do not appear in the over-all optimum ranking. The third part of the output is presented in tabular form showing the 30 best over-all designs in order of increasing total cost. Using his judgment and experience, the pavement designer can then select from these designs the one he will use for the pavement under consideration.

A limited sensitivity analysis was conducted under Project 1-10A to provide some indication of the influence of the individual variables on the output. Obviously there may be interaction between variables that were not considered during this study, and the results of the sensitivity analysis should be regarded only as an indication of trends identified by SAMP6. The soil support value of the subgrade was found to be one of the most important properties of the pavement from an initial construction cost standpoint. Variations in unit costs of materials, particularly with regard to surface course, can greatly influence total pavement cost and the ranking of different layered systems. This emphasizes the need for making careful cost estimates based on detailed consideration of likely contractor operations. The sensitivity analysis indicates that base and subbase material properties are most influential in moderate- to heavy-traffic conditions; in low-traffic conditions, the surface course properties have the greatest effect on total cost. Traffic delay costs of detouring around overlay operations are insignificant until congestion occurs, at which time they become enormous, sometimes doubling the total cost of the pavement. It is interesting to note that doubling the estimated equivalent 18-kip, single-axle loads, the interest rate, and the analysis period increased the total cost by only about 10 percent. This does not necessarily mean that these factors are of little importance in the design process but, rather, that the present models used in the system point to the need for greater emphasis on quantifying such factors as user costs and material properties of the subgrade and pavement structure.

## APPLICATIONS

One illustration of the kinds of evaluations that can be made with SAMP6 is a comparison of the economics of staged construction and planned rehabilitation versus the "no-overlay," or a strong initial construction, approach. An urban freeway being designed as asphaltic concrete for moderate traffic was analyzed for both staged construction and no-overlay approaches. The staged construction analysis designated the time to first overlay at 2 years and a minimum time between overlays of 5 years. The no-overlay approach designated the minimum time to first overlay at 20 years. Table 1 compares the optimum design for each of the two strategies.

Even though both design and management strategies provide equivalent serviceability to motorists, the initial construction cost of the no-overlay pavement is 39% greater than the staged construction approach and, after 20 years service, the no-overlay pavement would have a 22% greater total cost. The program predicts, in this case, that the cost of future overlays will largely be offset by the greater costs of routine maintenance for the no-overlay approach. User costs are minimal because of the moderate traffic anticipated. However, as indicated by the sensitivity analysis, doubling the traffic volume for this problem would substatially increase user costs and could easily result in the no-overlay approach having the lowest total cost.

Another illustration of use of the program involves the effect of fluctuating material costs on optimum design. A typical secondary road problem was run in 1973 when asphalt cost was estimated at $0.18 per gallon. It was run again in 1974 with the asphalt cost doubled. In 1973, before the energy crisis, the lowest total cost design selected by SAMP6 was 4 in. of asphaltic concrete over a prepared subgrade. During the 1974 energy crisis, the lowest cost design became a 1-in. asphaltic concrete surface course over aggregate base and subbase courses. The 1974 optimum pavement design cost was only about 10% above the 1973 optimum design, even though the cost of asphalt had doubled.

Use of the systems approach to pavement design and management, and more specifically the operational SAMP6 program, provides highway decision-makers with the capability for comprehensively selecting optimum strategies and updating decisions as conditions change. By using computer techniques, a large number of parameters and their interactions (as many as several thousand combinations for one problem) can be evaluated within realistic time and cost limitations. Optimization is normally based on lowest total cost over the analysis period, but other parameters--such as user costs, initial construction costs, use of materials, or rehabilitation programs--can be optimized by proper program control. The strategy selection capability primarily is a quantitative procedure for considering the long-term advantages and disadvantages of staged construction versus strong initial structural designs, thus providing a basis for more objective decision-making. The capability of quantitatively updating decisions is a unique feature of the approach. Existing pavements as well as those being designed can be analyzed in terms of optimization and strategy selection, and decisions affecting them can be revised in view of changes in material costs, material availability, funds availability, and traffic conditions.

An early indication from trial implementation of SAMP6 is that consideration of staged construction and planned rehabilitation is a vital element in the pavement design and decision-making process for the following reasons:

1. Available funds can be used to greater extent to provide the ultimate geometrics and subgrade support for serving present as well as future transportation needs.

2. For all but the most heavily traveled roadways, staged construction is likely to result in the lowest total cost over an analysis period of 20 or more years. Although the present federal-aid program, particularly with regard to the Interstate system, generally favors strong initial design with a minimum of future rehabilitation and maintenance, overlays and rehabilitation are becoming eligible for federal aid and future legislation may be more favorable to planned rehabilitation.

3. The rapidly increasing demand for highways can no longer be projected indefinitely. In urban areas in particular, automobile traffic

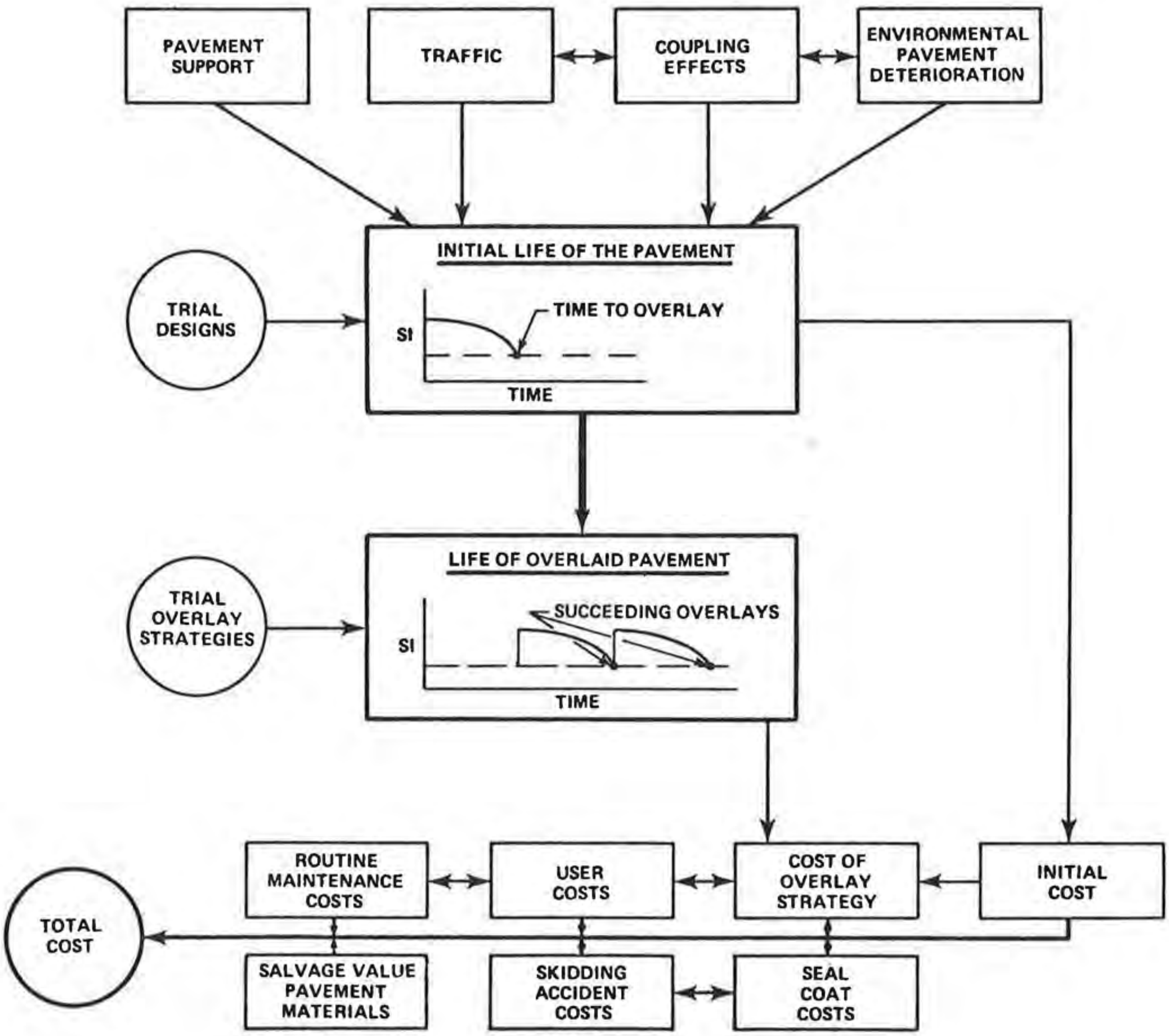


**FIG. I SCHEMATIC COMPUTATION DIAGRAM OF A PAVEMENT DESIGN SYSTEM**

possibly has peaked. Travel patterns could change substantially in the next 25 years. The investment of transportation funds in a pavement structure designed to carry traffic projected to continue increasing over the next 20 to 40 years seems questionable.

4. The seemingly unreasonable increase in cost of materials, in addition to the reduction in highway revenues because of the current energy crisis, results in the need for flexibility in decision-making. Staged construction permits maximum utilization of available materials and funds and provides a sound basis for future building programs if and when the energy shortages are resolved.

TABLE 1

COMPARISON OF OPTIMUM DESIGN FOR STAGED CONSTRUCTION vs NO-OVERLAY APPROACH

| Item | Staged Construction | No Overlay |
|---|---|---|
| No. of overlays (20 yr) | 4 | 0 |
| Costs ($/ sq yd): | | |
| Initial | 6.05 | 8.38 |
| Overlays | 2.30 | 0 |
| User | 0.08 | 0 |
| Routine maintenance | 0.12 | 1.68 |
| Total | 8.55 | 10.06 |
| Salvage value ($/ sq yd) | -1.10 | -0.96 |
| Present value total cost ($/ sq yd) | 7.45 | 9.10 |

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