

Microcomputer Linear Programming Model for Optimizing State and Federal Funds Directed to Highway Improvements

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Funding problems have been one of the major catalysts for implementing and improving the pavement management process. With a drop in anticipated federal funding levels, many states have been and will be required to raise additional state funds. At the same time, states need to recognize the increasing demands for preventive maintenance. Consequently, states need to ensure optimum use of all funds, as well as justify the levels of their requests. To investigate the most effective use of Maine's funding sources, the problem was modeled using linear programming (LP). A simple spreadsheet-based microcomputer LP code that incorporated available pavement management data was employed. The "benefit" measure used to evaluate the variety of available strategies was based on the performance concept of the AASHO Road Test. Actual data on the performance of flexible pavements in Maine were used to construct the models. Two network-level models were developed and applied to the state's Federal-Aid Primary system. One version established "target" miles of the various candidate strategies, and corresponding levels of service, in order to meet a variety of fiscal constraints. The second approach established optimum state and federal budget levels, and corresponding miles of improvement, to meet a variety of performance and resource criteria. The solutions were compared with the needs established by existing methods. They compared favorably and also provided a quick and simple means of evaluating various levels of state and federal budgets. The models also make it possible to support budget requests with objective data.

The pavement management process, introduced in Maine in 1981, initially concentrated on identifying needs to meet a series of top management constraints. More recently it has allowed the department to set priorities among systems, but it has not been used specifically to address the issue of cost-effectiveness of state versus federal programs.

In the Maine Department of Transportation, as in most if not all state highway agencies, recent funding levels have seldom been adequate to meet desired goals. Funding normally comes from both federal and state sources, but the question of how to make optimum use of this combination is seldom addressed.

Federal highway funds are apportioned to states in accordance with a variety of formulas. To obtain these funds, states must match the federal share with state funds in ratios that are dependent on how and where the funds are applied. If states fail to provide their share, the federal funds lapse. On the other hand, state funds used to match the federal share could be used

for state-funded activities including maintenance. What are the best uses for these state dollars? State matching funds generate federal funds on a more than one-to-one basis; therefore, it behooves the states to assure optimum use of the resulting funding package. Further complicating the issue is that projected allocations, resulting from the 1987 Surface Transportation Act, will be less than the amount from previous programs. The issue is complex and requires nontraditional forms of evaluation. In any agency, it becomes imperative that an optimization approach be implemented in order to maximize the return on taxpayer dollars.

STUDY OBJECTIVES

The major goal of this study was to develop methodology to examine the optimum use of both state and federal funds in developing a highway improvement program.

The problem was approached by using a "classical" linear programming (LP) approach to model the given objective. LP is a convenient way to model the allocation of resources because it seeks the best solution for a number of competing economic activities.

Introduction during the past few years of microcomputer-applied LP codes has now made it practical and relatively simple to adapt this approach to transportation budget issues. In any operations research study of a specific problem, six phases are generally recognized:

1. Formulate the problem by means of a problem statement,
2. Construct a mathematical model of the system,
3. Derive the solution,
4. Test the solution derived from the model,
5. Establish controls over the solution, and
6. Implement the solution.

This outline served as a guide in addressing the problem presented. Phases 5 and 6, although beyond the scope of this paper, would be required should the findings of this research lead to implementation.

PROBLEM STATEMENT

The Maine Department of Transportation has the choice of applying a variety of repair strategies on many highway sections; the problem is to determine how many miles of each strategy to perform on competing highway sections in order to

maximize the level of service provided, subject to the constraints of available federal and state funds, projected deterioration, and other applicable management policy.

STEPS TO A MATHEMATICAL MODEL

The construction of a mathematical model can be initiated by answering three questions:

1. What does the model seek to determine? In other words, what are the unknown variables of the problem?
2. What limitations (constraints) must be imposed on the unknowns to satisfy the model?
3. What is the goal (objective) that needs to be achieved in order to determine the best (optimum) solution for all of the feasible values of the unknowns?

These inquiries were instrumental in conceptualizing the model, formulating the approach, and defining the objectives.

APPROACHES CONSIDERED

The problem that was modeled addressed network-level as opposed to project-level activities. The approaches presented conform to definitions of the department's pavement management system (PMS). The outputs of the models (or unknowns) were designed to address the same goals that the existing PMS addresses at the network or statewide level.

In addition to identifying optimum funding levels or optimum use of limited funding, there were several other associated issues to be investigated. For example, if federal funds were not available, where would the cuts have to be made? If additional state funds could be identified, would they provide more benefit if assigned to state-funded projects or applied to match federal funds? Probably the ultimate question was "how efficient was the latest highway program?"

Two approaches were considered for this study. The first approach was to minimize total expenditures to meet the various resource and service-level constraints established by top management. In reality, this approach might not even lead to a feasible solution depending on the level of management constraints introduced. If that were the case, it would then provide an excellent mechanism for justifying the exact funding levels required to meet management guidelines as well as to establish the amount and source of additional funds required to make incremental improvements in levels of service.

The second approach considered was to maximize the benefits provided under given state and federal budget levels. With this approach, it would be possible to establish the benefits provided by various budget combinations and also to evaluate incremental increases in state, then federal, funding to determine which provided the best return on the dollar. It would also offer an opportunity to evaluate the recently approved program.

The decision variables, or unknowns, under both approaches would be the number of miles of the various strategies to be performed on the different categories of highways. It would then be possible to compare the number of miles with values developed by traditional methods to check for major inconsistencies.

Evaluating Options

Many constraints were common to both approaches. Under the minimizing cost approach, the objective function would be to minimize the total costs of all of the strategies considered. Sensitivity analysis would consist of examining the effects of unit costs on the solution. A second analysis could examine the effect of various service levels and the minimum expenditure needed to attain them. Under the maximization of benefits approach, the budget levels would enter as constraints and the objective function would be the resulting total of projected benefits at the suggested budget levels. Early on, "benefits" were recognized as potentially the weakest component of the models being considered. When constructing a model, it is important to examine the behavior of a solution in response to changes in the parameters of the system. This is especially important when they may be difficult to quantify accurately as is the case for benefits. In this case it is important to perform sensitivity analysis to study the behavior of the solution in the neighborhood of the estimated values. By making "benefits" the objective function, it would be possible to readily perform the required sensitivity analysis of the values employed and thus provide a way of judging the dependability of the models.

Sensitivity analyses could also be performed in the first approach. However, they would not be as convenient and easy to interpret.

Because there were significant advantages to each approach, a decision was made to examine both. In addition, because most of the components were similar, one model form could be easily converted to the other.

Data Requirements

As an aid to understanding the composition and function of the models, the data components are briefly discussed. Actual data were used so the results could be compared directly with those contained in the department's 1988-1989 Highway Needs Report (1) developed by the Pavement Management staff. This step is important and conforms to the fourth phase, noted earlier, that calls for checking the models' validity. A common method is to compare the results with some past data for the system being modeled. Because the models were intended to examine actual data, the comparison should reveal favorable results.

Highway Classification Groups

To classify the many miles of highway within each highway system, the existing PMS process aggregates highway sections to reflect various levels of traffic (high and low), standards (adequate and inadequate), and present pavement condition (good to poor). High traffic levels range from 3,000+ average daily traffic (ADT) on the Federal-Aid Primary system to 500+ ADT on the nonfederal state system. Standards of adequacy are based on pavement and shoulder width criteria as well as vertical and horizontal geometrics. The three-variable matrix results in 12 condition states or categories. Table 1 gives this configuration. Because a majority (99 percent) of non-Interstate pavements are bituminous, pavement type is not a variable. The small mileage of rigid pavements is handled on a case-by-case basis.

TABLE 1 HIGHWAY CATEGORIES

Traffic	Pavement Condition ^a	Standards	
		Adequate	Inadequate
Low	Good	A1	I1
	Fair	A2	I2
	Poor	A3	I3
High	Good	A4	I4
	Fair	A5	I5
	Poor	A6	I6

^aPavement ratings: good = 3.2 to 5.0; fair = 2.4 to 3.2; and poor = <2.4.

Benefit Measures Considered

This item, as noted earlier, introduced the most uncertainty into the models. Four potential measures were considered. Without a doubt, more could have been identified. The choice for this study was made after information obtainable from existing PMS records was considered. This is not to say that the method chosen was the best. As more data are accumulated and analyzed through the department's PMS activities, additional measures could be developed. The areas examined were

1. Reduction in future maintenance costs,
2. Improvement in structural integrity,
3. Reduction in user operating costs, and
4. Improvement in pavement performance.

Each measure was examined in view of how it could be incorporated to reflect benefits of a given strategy as well as provide the necessary measure of demand to which the sum total of all benefits (gain) had to be targeted.

After all of the options had been reviewed and available data were known, a decision was made to employ pavement performance as represented by a measure of a pavement's level of service.

Each of the other options had considerable merit. However, the data necessary for developing the appropriate benefit or demand measures, or both, were either unavailable or questionable. Pavement performance, on the other hand, was selected because there existed historical data on the projected life of the strategies employed in Maine as well the projected loss of service (or deterioration) of the existing highway network. In addition, because of the strong implied relationships between pavement condition and structural integrity and user costs, future correlations would allow those attributes to be examined when relationships became established.

MODEL DEVELOPMENT

After the various budget and system characteristics had been considered, a decision was made that the model or models constructed should be applied to one entire system in the state. It should be noted here that, although this study was of flexible pavements, rigid pavement could be examined using the same approach. The rural Federal-Aid Primary system was chosen because it contained significant mileage (1,826 mi) and had a sizable federal apportionment (\$28 million). In addition to the Primary apportionment, substantial surplus Interstate resurfacing, restoration, rehabilitation, and reconstruction (4R) funds were being considered for transfer to this system.

In Maine pavement condition is represented by two measures: distress and roughness. Because historical distress data were more complete and available, distress was chosen to represent level of service. Pavement condition is represented by a rating index of zero to five, with five being perfect. Pavement data collected and tabulated in the spring of 1986 were employed. These are the same data that were used to establish the needs and suggested program levels for the period being evaluated. There are at present eight strategies employed in the programming process. They range from maintenance resurfacing to total reconstruction. Table 2 gives a summary of all of the strategies along with the unit costs and range of life expectancies experienced.

TABLE 2 STRATEGIES, AVERAGE COST, AND RANGE OF SERVICE LIVES

Strategy	Abbreviation	Cost/Mile (\$)	Life (years)
Maintenance resurfacing	HHM	12,000	4-6
State light resurfacing	SLR	35,000	6-8
Federal light resurfacing	FALR	77,000	6-8
1 1/2-in. federal overlay	1 1/2 in.	160,000	10-12
Structural overlay	SOL	200,000	12-16
Light federal rehabilitation	RHBL	305,000	14-16
Heavy federal rehabilitation ^a	RHBH	550,000	16-18
Reconstruction	RCN	1,100,000	20

^aBy MeDOT definition, rehabilitation consists of varying levels of improvements within a project, ranging from local base and drainage repairs to reconstruction. Rehabilitation is considered a stopgap form of reconstruction.

The matrix given in Table 3 indicates the combination of highway categories and strategies. Cells in which strategies are not logical or practical have been eliminated and are shown blank. As an example, a federal overlay would not be placed on sections with inadequate standards, nor would a section that met geometric and structural standards be totally reconstructed. This step helped reduce the number of variables significantly from 108 to 48. Also given in this table are the total miles in each category, the average rate of loss or drop in pavement condition for the category, and the total loss of condition for all miles in the category.

Determining Model Coefficients

Under the pavement serviceability concept of the AASHTO Road Test (2), performance is defined as the accumulated serviceability of a pavement over its life. Figure 1 shows a typical curve indicating past and projected service levels. Graphically, performance is the sum of the area under the performance curve. The projected remaining performance of a section of highway is, therefore, the remaining area until a terminal state is reached. As a pavement section deteriorates, it consumes performance. This represents loss and is represented by the area for a given increment of time. The program period for this study is 2 years. The total projected performance of a highway system at time t is, therefore, the sum of the areas of each individual section from t to t_p . Conversely, the projected

TABLE 3 MATRIX OF STRATEGIES AND HIGHWAY CATEGORIES

Strategy	Highway Category ^a											
	A1	A2	A3	A4	A5	A6	I1	I2	I3	I4	I5	I6
State												
Do nothing	X1	X2		X3	X4		X5	X6		X7	X8	
HMM		X9	X10		X11	X12		X13	X14		X15	X16
SLR		X17	X18		X19	X20		X21	X22		X23	X24
Federal												
FALR		X25	X26		X27	X28						
1 1/2 in.		X29	X30		X31	X32						
SOL		X33	X34		X35	X36						
RHBL								X37	X38		X39	X40
RHBH								X41	X42		X43	X44
RCN								X45	X46		X47	X48
Miles	258	163	69	374	180	72	140	171	95	156	78	71
2-year loss	0.30	0.30	0.60	0.25	0.40	0.55	0.45	0.40	0.55	0.80	0.50	0.75
Total loss	80	50	42	96	72	38	64	69	54	132	40	54

^aFrom PMS data base.

loss on a system is the sum of the areas for each section between t and $t+2$.

Using formulas adopted during the developmental stages of pavement management, the total projected pavement condition, at any time t of each strategy, can be determined using the general form of equation:

$$PCR_t = I - mts/20 \quad (1)$$

where

- PCR_t = pavement condition at time t ,
- m = coefficient constant (0.66),
- t = time,
- s = variable exponent = 1.9/log service life, and
- I = rating immediately after improvement.

and the projected performance of an improvement is therefore

$$P = \int_0^L [(I - S_t) - (mts/20)] dt \quad (2)$$

where

- P = performance,
- S_t = terminal serviceability value, and
- L = service life of treatment.

By using Equation 2, and the projected life expectancies for each strategy combination (X_8 to X_{48}) of Table 2, performance values were calculated. These values represent the projected area of performance from t_0 to t , as shown in Figure 1. Two values for terminal serviceability S_t were employed. They are 2.2 and 2.8 and correspond to those of Categories A2, A5, I2, and I5 and A3, A6, I3, and I6, respectively. These calculated values of total projected performance or benefits are given in Table 4. Also given is the sum of projected loss in performance for each category:

$$\text{Loss} = 2\{[PCR_t - (L_2/2)] - S_t * M\} \quad (3)$$

where

- PCR_t = mean pavement condition rating of category at time t ,

- L_2 = condition loss for 2 years,
- S_t = 2.0, and
- m = total miles in category.

Establishing Constraints

In the minimizing cost approach, the aim was to develop the appropriate level of state and federal funding to meet the initial directives of top management. This paralleled the efforts of the PMS process to address the department's needs and also conformed to the results presented in the Highway Needs Report (1). Specifically, these directives were that

- The total projected deterioration would have to be offset by improvements of equivalent total performance so as to maintain the level of service.
- The average pavement conditions would also be maintained for 2 years.

The PMS process initially identified a level of need referred to as "optimum." The term optimum as used here is intended to mean "preferred" budget level and should not be confused with the definition of optimum as applied to LP solutions. To attain the preferred level, two additional limitations were introduced:

- All deterioration in the poor category had to be offset by primary strategy as opposed to secondary or tertiary options.
- All improvements generated had to guarantee a balanced program over a 20-year analysis period. This was to promote a future steady-state condition by building in the next improvement at the point of terminal serviceability (for example, a strategy with a 12-year projected life is accounted for again in 12 years and not deferred).

In constructing the first model, the four points just mentioned were incorporated as constraints. For future reference, they are labeled in order:

- Performance,
- Pavement condition,

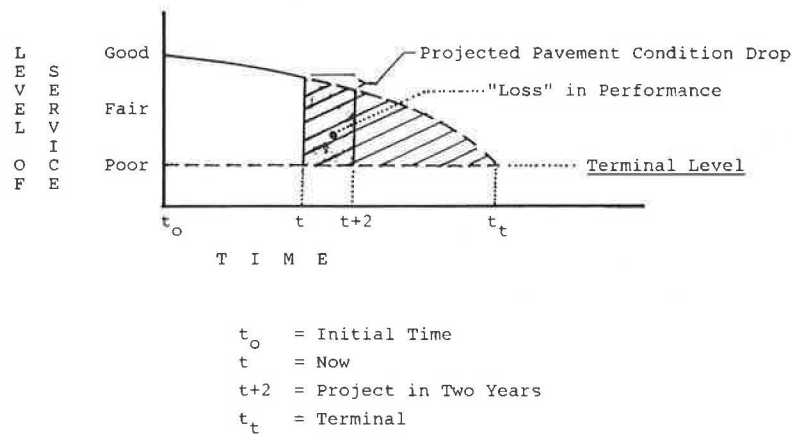


FIGURE 1 Performance and deterioration concept.

TABLE 4 BENEFITS OF EACH STRATEGY AND CATEGORY COMBINATION

	Highway Category											
	A1	A2	A3	A4	A5	A6	I1	I2	I3	I4	I5	I6
Strategy												
Do nothing												
HMM		4.4	5.8		4.4	3.6		4.4	3.0		2.4	3.0
SLR		5.8	7.6		8.5	9.7		5.8	5.3		4.4	5.3
FALR		10.9	14.5		10.9	11.2						
1½ in.		15.4	21.7		15.4	17.8						
SOL		19.6	26.6		19.6	23.7						
RHBL								17.4	23.7		17.4	23.8
RHBH								19.6	26.8		19.6	26.8
RCN								24.0	33.0		24.0	33.0
Loss of performance ^a	929	196	42	1346	216	38	476	205	54	484	86	54

^aTotal 2-year loss of performance = 4126.

- Deterioration, and
- Project cycle.

Several other constraints also had to be employed to ensure that the model did not generate an unbounded or illogical solution. To start with, the model had to specify the number of eligible miles within the various groups to ensure that the solution would not exceed the limits of available miles. This constraint is referred to as Miles. To model some of the real-world restrictions, it was also necessary to specify a minimum number of miles of reconstruction and a maximum number of miles of resurfacing. The first constraint accounted for committed projects from previous programs for which all preliminary engineering and justifications had been completed. The second constraint accounted for the resource limitations of the department and the paving industry. Because the weather severely restricts the season during which paving operations can occur, finite limits do exist for this part of the highway industry. The values used for this study are based on engineering judgment and historical data. They may be considered arbitrary, but they are real. These limitations are represented by constraints called Min Rcn and Max O'Lay, respectively. Before the model was given its final form, it was recognized that, ideally, a maximum number of miles in the poor categories should be addressed. The number of surplus poor miles in each solution

represented miles subject to potential maintenance expenditure. Although this was not, and could not be, included as a constraint, each solution was examined to quantify this potential.

OPTIMIZING BUDGET LEVELS

By employing Tables 2–4, the following model was developed:

$$\text{Minimize budget } Z = \sum_{i=1}^9 \sum_{j=1}^{12} C_{ij} X_{ij} \quad i = 1, 2, \dots, 9 \\ j = 1, 2, \dots, 12$$

where X_{ij} is the amount of Strategy i performed in Category j and C_{ij} is cost of Strategy i performed in Category j , subject to the following constraints:

1. Pavement condition: The sum of improvements in condition must equal or exceed the total loss in each category (Table 3).
2. Performance: The sum of improvements in performance must equal or exceed the total loss in performance in each category.
3. Deterioration: The sum of improvements in performance for Categories I3 and I6 must be derived from Strategies 7, 8, or 9 of Table 2.

4. Project cycle: The total number of miles of each strategy for each category times its expected life must equal or exceed the total miles in the category (Table 3).

5. Miles: The total number of miles selected in each category cannot exceed the total number of available miles (Table 3).

6. Max O'Lay: The total number of miles of each resurfacing strategy (Categories 2–6) must not exceed the total available miles divided by the life expectancy in bienniums.

7. Min Rcn: The total miles of Strategies 7, 8, and 9 performed in Categories I2, I3, I5, and I6 must equal or exceed a threshold value (to be entered).

The LP code employed for this study is a spreadsheet-based version called "What's Best!" (3). It was selected because the models could be created in a free format on available spreadsheets using linear formulas. It is based on the well-known LINDO optimization code. The completed model was then applied.

Because this initial version constrained performance within each of the highway categories, it was significantly more restrictive than the traditional PMS approach of total performance only. To examine the effects of relaxing the individual categories (Constraint 2) a series of iterations was run employing percentages (90, 80, and 70 percent) for each category until the total performance gain equaled or approached total performance loss. In some cases it was not possible to reduce total gain to the level of total loss because the performance constraints became nonbinding. After this exercise was completed, another iteration was employed that paralleled the method used in the Needs Study and is referred to as "basic" needs. This consisted of substituting secondary and tertiary strategies for two-thirds of the deterioration in the poor category (Constraints 3 and 7). Even though secondary and tertiary strategies were employed, pavement conditions could be maintained during the 2-year period because more miles were addressed. However, total performance levels were lower.

A summary of the results of both of these exercises is given in Table 5 along with the corresponding values obtained in the Needs Study. The actual miles of each strategy predicted by the various models are given in Table 6 along with those developed in the Needs Study. Two observations are made at this time. First of all, the results obtained, although similar to those in the Needs Study, indicated a significantly higher portion of state-funded work. This is because this model did not differentiate between sources of funds but merely sought the lowest total cost solution. This favored state-funded projects. Second, attention is directed to the small number of miles of 1½-in. overlay predicted by the models. The main explanation for this is that performance loss for Columns A3 and A6 of Table 4 did not turn out to be a binding constraint; therefore, the model chose the lower-cost option (FALR) to minimize cost (X26 and X28 instead of X30 and X32).

MAXIMIZING PROGRAM PERFORMANCE

After the minimizing cost approach was completed, the second approach was employed whereby the objective function was to maximize benefits for given budget levels. This required minor changes in the original model, the first of which was to remove

TABLE 5 COMPARISON OF MINIMIZING COST MODEL OPTIONS

	Budget Level (\$ millions)		Performance
	State	Federal/ State	
Optimum PMS	2.5	50.4	N/A
Basic PMS	2.9	37.3	N/A
Model			
Deterioration constraint	7.0	47.5	5365
Match total loss only	4.1	46.5	4733 ^a
Relax deterioration	8.6	29.7	4788
Match total loss only	5.8	38.8	4130

^aMinimum level (performance no longer binding).

four constraints dealing with meeting performance criteria. This now became the objective function. A second change was made that required adding budget levels as constraints. These changes are represented as

$$\text{Maximize performance } Z = C_{ij} X_{ij} \quad i = 1, 2, \dots, 9 \\ j = 1, 2, \dots, 12$$

where X_{ij} is the amount of Strategy i performed in Category j and C_{ij} is improvement in performance generated per unit of X_{ij} .

Constraints 1 and 3–7 of the original model were retained. The two added constraints were

8. State funds: The total of all miles of Strategies 2 and 3 shall equal some assigned value.

9. Federal funds: The total of all miles of Strategies 4–9 shall equal some assigned value.

The first exercise performed under this approach was to examine the feasibility of attaining a solution employing just federal funds. It was not possible within reasonable limits to obtain a feasible solution. (Feasibility occurred at \$85 million.) At this point, state funds were introduced. After repeated runs it became apparent that there existed a minimum sum of state funds with which a reasonable feasible optimum solution could be expected. This value was found to be \$3.1 million and resulted in a feasible solution when a federal funding level of \$50.0 million was introduced. A reduction to \$49 million resulted in infeasibility. At this point it was decided to examine the effects of increased funding. Federal levels up to \$60 million and state levels up to \$6 million were independently examined. These results are discussed later.

At this point, constraints were relaxed to reflect secondary and tertiary strategies as was done with the original model. Feasibility was attained at \$37 million in federal and \$3.7 million in state funds. Results of this and the initial run are given in Table 7 along with PMS results. As indicated, these compare favorably. Table 8 gives a summary of the various miles of each strategy suggested by the corresponding options. With the exception of the 1½-in. overlay, there is a striking similarity in the miles of each strategy compared with the corresponding PMS values. One more thing is worth noting about the data in Table 7. Because the traditional PMS analysis did not quantify the levels of performance, it estimated

TABLE 6 COMPARISON OF MILES OF STRATEGIES, MINIMIZING COST MODEL

Strategy	Optimum	Basic	Full Deterioration		Relax Deterioration	
			Loss by Category	Total Loss	Loss by Category	Total Loss
HMM	168	179	187	226	252	268
SLR	17	17	137	41	160	73
FALR	92	122	117	115	117	115
1½ in.	85	90	42	37	42	37
SOL	13	15	0	0	0	0
RHBL	33	12	63	63	32	32
RHBH	7	4	10	10	3	3
RCN	12	3	17	7	2	3
Total	427	442	573	499	608	530

TABLE 7 COMPARISON OF MAXIMIZING PERFORMANCE MODEL OPTIONS

	Budget Level (\$ millions)		Performance
	State	Federal/State	
Optimum PMS	2.5	50.4	N/A
Basic PMS	2.9	37.3	N/A
Model			
Deterioration constraint	3.1	50.0	4897
Relax deterioration	3.7	37.0	4530

the optimum level as status quo when in reality the figure represents a system gain of about 5 percent.

At this point, as with the initial analysis, state and federal funds were incrementally increased independently. The results of that exercise will be discussed later.

To investigate the impact of not specifying a minimum amount of reconstruction, a separate evaluation was performed with Constraint 6 removed. In addition, secondary and tertiary strategies were allowed to provide all of the required performance for Categories I3, I5, and I6. When the model was applied to the \$3.7 million state projects level, a feasible solution was derived at a federal level of \$35 million. Surprisingly, reconstruction options still entered the solution. This occurred in Categories I3 and I5 so the constraining number of miles of resurfacing would not be exceeded.

All of the solutions from the previous maximization model were examined to determine how many miles in the poor category were not addressed. These were potential miles for some form of major maintenance activity to meet the concerns

noted earlier. The data are plotted in Figure 2. Attention is directed to the plot representing the \$37 million federal level. As state funding levels were increased from the minimum level, potential maintenance miles actually increased temporarily. This is because the model was maximizing performance and not concerned with the number of surplus miles. Had the maximum number of surplus miles been made a constraint, the solution, for the same number of dollars, would have resulted in a lower value for total performance.

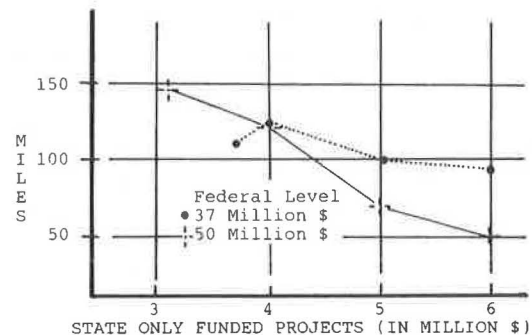


FIGURE 2 Poor miles not addressed at different levels of funding.

DISCUSSION OF RESULTS

Minimizing Cost

The various analyses produced several results worth noting. Portions of every constraint type were influential in each solution. The most prevalent constraint was the one requiring

TABLE 8 COMPARISON OF MILES OF STRATEGIES, MAXIMIZING PERFORMANCE MODEL

Strategy	Optimum	Basic	Full Deterioration	Constraint Relaxed
HMM	168	179	183	211
SLR	17	17	26	33
FALR	92	122	121	121
1½ in.	85	90	19	33
SOL	13	15	29	30
RHBL	33	12	63	40
RHBH	7	4	10	3
RCN	12	3	7	2
Total	427	442	458	473

pavement conditions to be maintained for the 2-year period. Performance criteria were nearly as significant but not necessarily for the same categories of highways. Where performance was not binding, the model chose the lower-cost strategy, unless it exceeded the available supply of miles.

When the performance constraint was relaxed to reflect total performance in lieu of performance in each category, the majority of reductions came at the expense of state-funded improvements. Federally funded improvements could not be cut because they were necessary to maintain average pavement conditions.

To examine the sensitivity of the unit cost coefficient of the 1½-in. overlay on the solution, a series of trials was made at different unit costs. That exercise indicated that unit cost had no effect until it was reduced by more than 30 percent. Even though the strategy provided more performance (profit) it did not enter into the solution because it consumed too much resource (money).

Maximize Performance

When the model was revised, a series of other things became evident. The most significant was that a minimum amount of state-funded projects was absolutely necessary in order to approach meeting the initial constraints with reasonable federal funding levels. Using both the full and relaxed deterioration constraints, it was possible to identify an appropriate level from which incremental increases of both state and federal funds could be evaluated. Figure 3 shows a plot, originating at these minimum levels, of benefits at increasing levels of state funds only, and then federal funds. The plot normalizes each approach by examining total state dollar demands. This was based on a 30 percent state match for federal funds added to the state-funded projects. That exercise was performed to determine the optimum use of additional funds. As can be seen in Figure 3, performance levels were slightly, but not significantly, better when applied to federally funded projects.

A constraint was introduced to specify a minimum number of miles of reconstruction; had it not been, the model would have still specified an amount equal to about 75 percent of the dollar requirement identified in the basic PMS level.

The final analysis consisted of evaluating the actual program. The approved budget for highway-related improvements was \$2.6 million of state-funded work and \$51.7 million of federal aid projects. This is quite similar to the optimum level suggested. Using the maximization of performance model, and assigning the total miles of each strategy as constraints, resulted in a projected performance total of 4125. This approximates the amount needed to maintain the level of service. It is interesting to note, however, that had the miles of reconstruction been cut back, say to the optimum level, then there could have been an improvement of 5 percent generated with the same funding level.

CONCLUSIONS

The following key points document the success of this investigation:

- Although both models were successful, the maximizing performance model best replicated data from the department's most recent highway needs analysis.
- The maximization of performance model proved to best optimize total state dollars.
- It is possible to document the need for minimum budget levels to meet management constraints with either model.
- It is possible to examine incremental increases in state or federal funding, or both, and to determine the best use of additional funds with the maximizing performance model.
- When the best use of additional state funds was examined, it did not appear to matter (for performance) whether they were applied to state or federal projects. However, program configurations were noticeably different.
- Trying to meet the 100 percent performance requirement for each category with the minimizing cost model appears too restrictive.
- The benefit measure employed, using the performance concept, does not appear to be sensitive to small variations.
- The physical limitations on performing resurfacing strategies has as much effect as any other factors in determining the configuration of a program.
- Major system improvements would require significant increases in resurfacing activities. This could necessitate some changes in policy areas that address the various resurfacing programs.

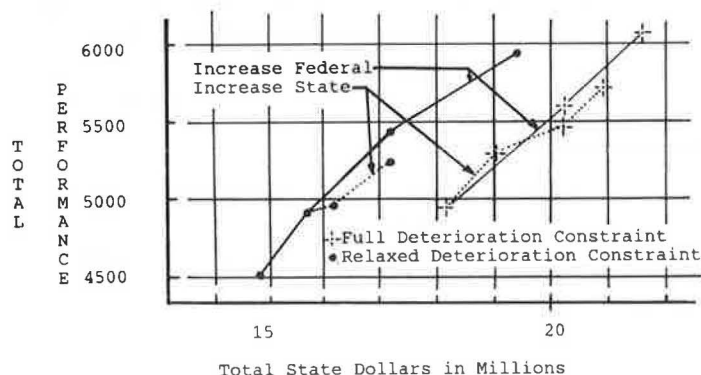


FIGURE 3 Performance for increasing state or federal projects compared with total state dollar demands.

- The low benefit-cost return of the reconstruction strategies suggests that it might be best to perform the analysis in three phases. Phase 1 would optimize all strategies without specifying a minimum number of miles of reconstruction. Phase 2 would optimize the balance of reconstruction strategies to meet management guidelines. Phase 3 would then use the optimum results of Phase 2 as input to re-assess Phase 1.

- The ease with which these models have been able to address a variety of questions suggests that they are far superior to the manual methods now employed.

- The budget as applied in the recent program maintains level of service and is a feasible but not optimum solution for the funds available, if to maximize performance is the objective.

RECOMMENDATIONS

- The models presented here, or some form thereof, should be made part of the department's pavement management process.

- The models should be tested with data from the other major systems.

- The suboptimization approach suggested earlier should be examined as an alternative to arbitrarily relaxing constraints.

- Testing of the models should enable these models, or a variety thereof, to be used in analyzing the needs for the next highway improvement program.

- It is further recommended that, when the next analysis of needs is presented, they include the incremental analyses, as

presented here, so that top management can appreciate the alternative approaches that the models present.

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