Optimization Enhancements for an Integrated Bridge Management System

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The optimization methodology used in a modular bridge management system (BMS) is described. The optimization module minimizes cost subject to top management's performance objectives. It is a Markovian-based system that stratifies the bridge network to improve degradation predictions. Graphical displays are given that illustrate the results of the BMS, providing an optimal path from current conditions to the desired goals. The system is solved using linear programming on the network level. The use of Lagrange methods and parametric programming allows an efficient integrated solution of the large network optimization in this BMS. This BMS is part of an overall highway maintenance management system, which integrates a pavement management system, a nonpavement management system, and a bridges and structures management system (B&SMS). The B&SMS includes optimization of bridges, tunnels, and culverts. The BMS is the bridge portion of the B&SMS.

Bridges are constructed of one or more spans that vary in length and width from bridge to bridge and can exhibit considerable variations in condition from span to span. Bridges can be rated and modeled in segments (a superstructure span with an abutment or pier). The many components of a bridge may be individually rated on a span-by-span basis and modeled as three structural elements (desk, superstructure, and substructure) at the network level in a bridge management system (BMS). Functional deficiencies such as inadequate load capacity and insufficient deck width may also be included.

The BMS is not dependent on having network data on spans, but the system is designed to accommodate such data. If information is only available for the entire deck, superstructure, and substructure (a condition that is common in the United States), the BMS will operate with this level of information at the network level.

Figure 1 shows the modules that this BMS comprises. The modules have been described by Harper et al. (*1,2*). The condition module uses surveyed condition rating data to derive condition states that characterize the overall condition of each bridge segment. Condition modeling begins with the surveyed condition rating (SCR) values assigned to the bridge components on a span-by-span basis. The following scale is being used by the Kingdom of Saudi Arabia; however, any similar scale, such as the 0 to 9 scale used by the FHWA, can be accommodated.

Rating	*Definition*
7	Like new
6	Good condition
5	Insignificant deterioration
4	Minimum adequacy
3	Not functioning as designed
2	Structurally inadequate
1	Potentially hazardous
0	Beyond repair

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The SCR values of the components of the deck (e.g., deck surface and deck structure), superstructure (e.g., primary and secondary members), and substructure (e.g., pedestals and capbeams) are used to derive composite condition index (CCI) values for each structural element; CCI values are, in turn, translated into condition levels. The various configurations of condition levels are used to construct the core condition states. Equations convert the SCR values to the CCI values. User-defined thresholds can be incorporated so that when a feature is rated at, say, less than 4, the CCI value would be modified by or assigned the value of the lowest SCR. Different equations are used for certain bidge types (*1,3*).

The various combinations of CCI ratings for the structural elements making up each segment are used to define core condition states that represent the overall condition of that segment. The CCI values are translated into one of four condition level descriptors for each of the three elements, according to the following scheme:

Range of CCI Values	*Condition Level*
From 6 to 7.00	Good
From 4 to 5.99	Fair
From 2 to 3.99	Poor
From 0 to 1.99	Critical

Core condition states are defined as possible combinations of condition levels for the elements that make up the structural segment. There are 64 (4^3) core condition states. Additional parameters are added depending on the needs of the organization implementing the BMS. Typical examples include element-age parameters (e.g., superstructure age) or various functional deficiency parameters (e.g., insufficient deck width).

The maintenance and rehabilitation (M&R) scopes module contains 40 M&R scopes. The impact of each M&R scope depends on the current condition state of the segment. This is modeled in the prediction module described in following paragraphs. The M&R scopes provide input to the prediction, cost, optimization, packaging, and comparator modules.

The prediction module for structural degradation develops and updates estimates of transition probabilities that are defined as the probability that a structural segment in Condition State i in Stratum s will be in Condition State j in 1 year, given M&R Scope a. These estimates are updated each year with new survey data for each stratum using a Bayesian up-

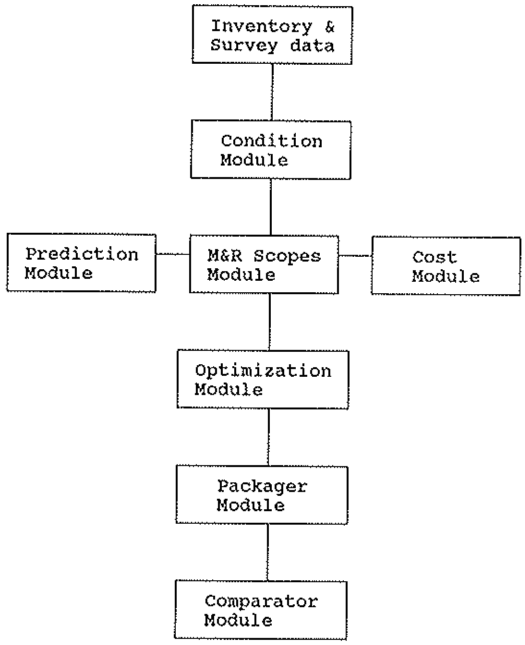

FIGURE 1 Structure of BMS.

dating procedure (*2,3*). The cost module uses historical cost data, condition states, M&R scopes, and other inputs to calculate M&R scope costs.

The optimization module has three network level models based on Markovian decision models using linear programming techniques (*2,3*). Subject to the desired performance goals in the optimization, it is the interaction of cost and transition probabilities that determines the optimal (minimal cost) policy. The three models are as follows:

1. A steady-state model to establish steady state minimum cost goals for each stratum,
2. A multiyear model to optimize expenditures within a desired time horizon leading to steady state for each stratum, and
3. A financial exigency model to force the total network (all strata) to meet a specified budget if sufficient funds are not available.

These models provide their results in terms of the proportions of each stratum that should receive various maintenance scopes for different condition states. The first two models are similar to the Arizona pavement models (*4*) in mathematical structure. Strata have been developed to group bridges that exhibit similar degradation patterns, and that have approximately the same M&R scope costs.

The packaging module packages the optimized network solutions into individual work projects. In the project level analyses by the packager, maintenance costs identified by the optimizer are more accurately assessed using actual material quantities and contractor prices.

The comparator module serves as quality control on the performance of the BMS. It provides necessary comparisons of both cost and predictive capabilities of the models against actual experience when the BMS solutions are implemented.

ANNUAL USE OF BMS

This section briefly describes the steps in the annual usage of BMS. To supplement Figure 1, Figure 2 shows the flow from one optimization model to another. Management input, cost parameters, transition probabilities, and condition survey data are necessary to run the suite of models. This process is iterative. Looping backwards may be necessary if satisfactory results are not obtained. The BMS annual usage scenario has the following steps (*2,3*):

1. Perform the condition survey and update the transition probabilities.
2. Make policy decisions regarding performance objectives.
3. Run the steady state optimization model for all strata. If the resulting steady state budget is acceptable, the output of the steady state model is used to develop constraint equations for the multiyear model. If the steady state budget is not acceptable, then management has to lower the performance objectives set in Step 2 and rerun the steady state optimizer. The final result of this model becomes a goal to be reached in the last year of the planning horizon for the multiyear model.
4. The multiyear model is solved for all strata to determine the optimal maintenance policy and the expected expenditures for each year in the planning horizon.
5. If the budgeting requirements from the multiyear model are too high, then the financial exigency model is run. The financial exigency solution yields the optimal first-year maintenance policy that stays within the first-year budget while at the same time computing the resulting additional expenditures needed to successfully achieve the performance objectives for the remaining years of the planning horizon.
6. Run the packager module to divide the M&R scopes into the detailed maintenance actions that are necessary for the selected bridge projects.
7. At the end of the fiscal year, the comparator module is run to provide feedback on the performance and implementation of the BMS.

BMS NETWORK OPTIMIZATION MODULE

As described earlier, the three optimization models are the steady state model, the multiyear model, and the financial exigency model. The steady state model is used to establish the long-term goals that provide targets for the multiyear and financial exigency models. The multiyear model addresses the year-by-year maintenance needs for the planning horizon. The steady state and multiyear models solve separate linear programs for each stratum. The financial exigency model imposes a network-wide budget constraint across all strata if insufficient budget is available to satisfy the sum of the individual stratum multiyear models.

The optimization models are used to develop a set of maintenance plans for a bridge system over the desired planning horizon. The steady state model described by Harper et al. (*2,3*) provides the goals for the final year of the multiyear model. Results from the steady state model were provided by Harper et al. (*5*). Similarly, the complete mathematical description for the multiyear model is provided by Harper et

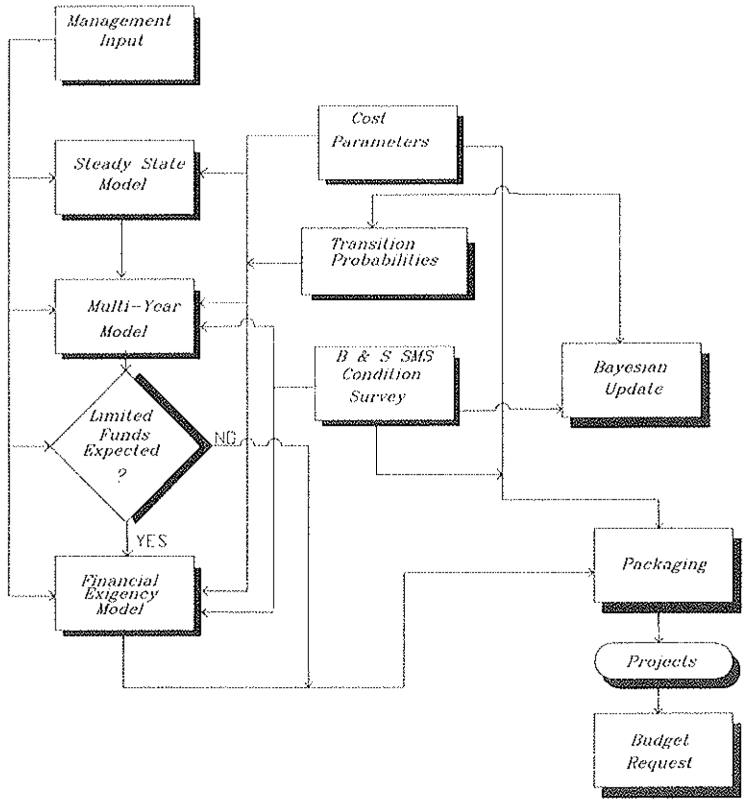

FIGURE 2 Interconnection of optimization models.

al. (*2,3*). Selected parameters from the multiyear model that are important in the subsequent financial exigency section are as follows:

- I = (1, 2, . . . , n), index set of condition states.
- S = (1, 2, . . . , m), index set of bridge strata.
- M_i = (a_1, a_2, . . . , a_{m_i}), index set of feasible maintenance Scopes a for bridge segments in Condition State i.
- $C_{ia}(s)$ = average cost of applying maintenance Scope a to one bridge segment in Stratum s and Condition State i.
- $N(s)$ = number of segments in Stratum s.
- r = discount rate (= 0.0 in this paper) for computing net present value.
- $w^t_{ia}(s)$ = proportion of the segments in Stratum s that is in condition State i and should receive maintenance Scope a in Year t. These are the optimization output decision variables.
- $E^t(s)$ = expected expenditures in Year t in Stratum s.

The multiyear optimization model for Stratum s in which T (= 6 for the runs in this paper) represents the year in which the steady state goals are met follows:

$$\text{Minimize} \sum_{t=1}^{T-1} \sum_{i \in I} \sum_{a \in M_i} (1 + r)^{1-t} w^t_{ia}(s) C_{ia}(s) \tag{1}$$

The objective function given in Expression 1 minimizes the average present cost per segment of maintenance over the time horizon of interest. To get $E^t(s)$ (the necessary budget for Stratum s for a given Year t), the following calculation is necessary:

$$E^t(s) = N(s) \sum_{i \in I} \sum_{a \in M_i} w^t_{ia}(s) C_{ia}(s) \tag{2}$$

Selected condition states are designated desirable or undesirable. Top management sets goals (lower bounds for desirable and upper bounds for undesirable) for each year of the planning horizon. The multiyear model results may be summarized by the optimal desirable and undesirable percentages that are predicted from the model. Figures 3 and 4 show the desirable and undesirable percentages that resulted from a typical multiyear optimization for a given stratum.

FINANCIAL EXIGENCY MODEL

When the multiyear model is run for all strata, the sum of the first year budgets from each stratum may exceed the available network budget. When this condition occurs, the financial exigency model is used. The financial exigency model links all strata together using Lagrange methods on a first-year network budget constraint. It would not be efficient (or feasible with some linear programming packages) to jointly solve the network optimization problem by pooling all the separate stratum linear programs. The use of Lagrange methods allows this problem to be solved in an efficient, straightforward manner.

The purpose of the financial exigency model is similar to that of the multiyear model, but it also incorporates the net-

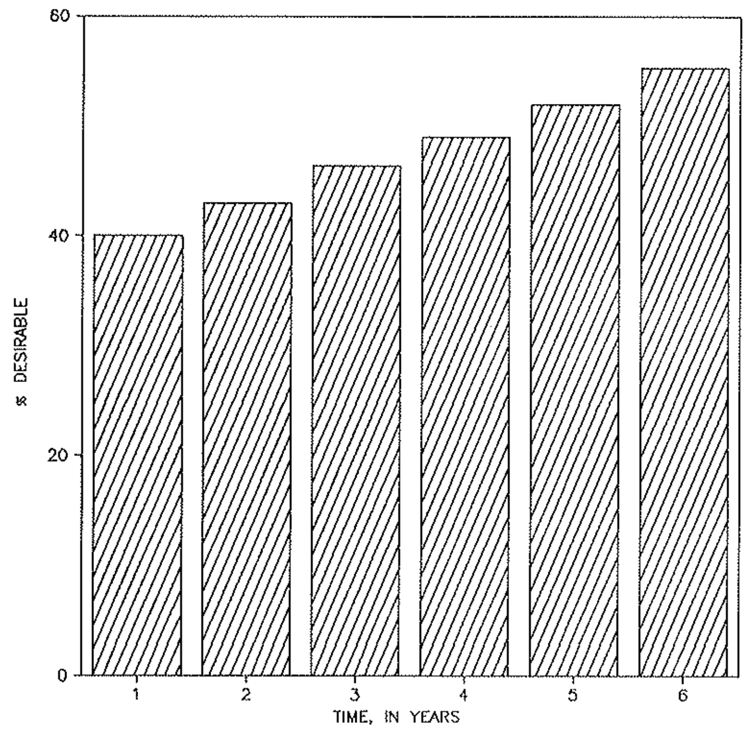

FIGURE 3 **Desirable percentage versus time.**

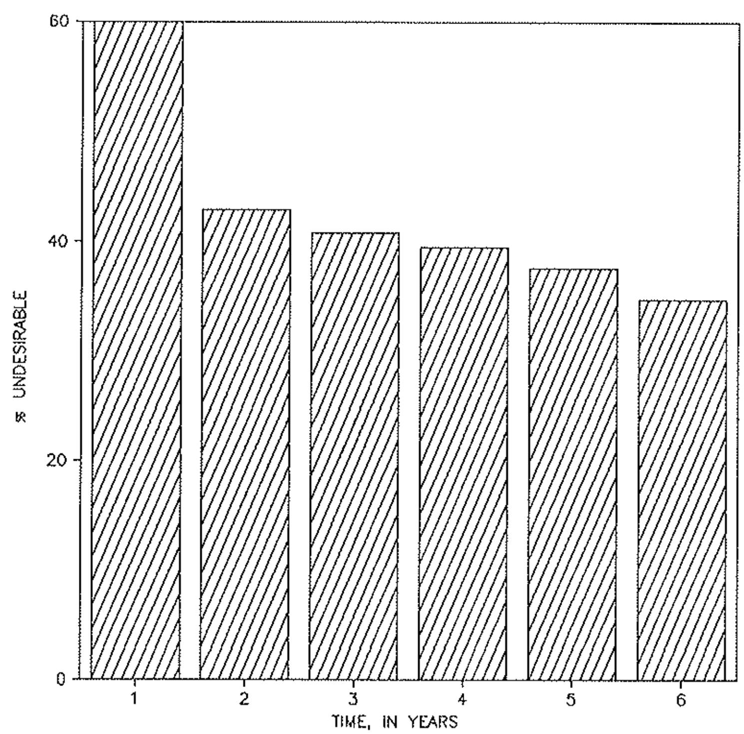

FIGURE 4 **Undesirable percentage versus time.**

work budget constraint for the first year of the planning horizon. Although the financial exigency model combines all strata together through the budgetary constraint, it decomposes the overall problem into linear programming problems for individual strata. The financial exigency model also allows the relaxation of the second-year goals if necessary to meet the first-year budget target. The financial exigency model objective function in Expression 3 is solved by determining the optimal value for the Lagrange multiplier α (*6*). If necessary, there are three phases (A, B, and C) of the financial exigency model that can be used to find an optimal solution that meets the available first-year budget. The objective function for this model is as follows:

Minimize

$$\sum_{s\in S} N(s) \sum_{i\in I} \sum_{a\in M_i} \left[\sum_{t=2}^{T-1} (1 + r)^{1-t} w_{ia}^{t}(s) C_{ia}(s) + \alpha w_{ia}^{1}(s) C_{ia}(s) \right] \quad (3)$$

subject to the constraints of the multiyear model for all $s \in S$, and with β^1 = available budget for the first year.

Different values of α will yield solutions that expend different amounts in year one. If for a given α, the solution prescribes a policy that expends too much money in the first year, a new solution can be obtained for a larger value of α that will expend a smaller amount in Year 1. For $\alpha = 1$, this objective function is identical to the multiyear model.

The value of α that produces the solution in which the total of all first-year expenditures among the strata is as close to (but less than or equal to) the first-year budget, β^1, results in a solution that is a globally optimal for the original financial exigency model (*6,7*). The first-year budget is a monotonically decreasing function of α.

Parametric programming on the objective function allows the financial exigency problem to be solved with minimal computational burden. In order to make the financial exigency objective consistent with parametric programming features found in some linear programming packages, the objective function in Expression 3 may be rewritten as Expression 4:

Minimize

$$\sum_{s\in S} N(s) \sum_{i\in I} \sum_{a\in M_i} \left[\sum_{t=2}^{T-1} (1 + r)^{1-t} w_{ia}^{t}(s) C_{ia}(s) + (\alpha_{\min} + \Theta) w_{ia}^{1}(s) C_{ia}(s) \right] \quad (4)$$

subject to multiyear constraints for all $s \in S$.

Thus, α has been replaced by $(\alpha_{\min} + \Theta)$. For Phases A and B, $\alpha_{\min} = 1.0$, whereas $\alpha_{\min} < 1.0$ for Phase C. Then Θ will range from 0.0 to $\Theta_{\max}$ ($\Theta_{\max}$ may be different for each phase) for the financial exigency runs.

Before describing the financial exigency algorithm, a brief summary of each phase is as follows:

- Phase A. The Year 2 goals are the same as the multiyear model.
- Phase B. Relaxes the Year 2 goals so that the current percentages desirable and undesirable (on the basis of the condition survey) are maintained.
- Phase C. Completely removes the Year 2 goals and attempts to spend as much money as possible while meeting the network level budget.

The goals referred to are the percentages desirable and undesirable that were set by top management for the multiyear model. One of the advantages of the three phases is that it is not necessary to go back to top management and request revised goals. The goals specified by top management are assumed to have had Year 2 goals that improved on the current conditions found in the stratum. If this is not the case, then Phase B may be skipped.

The algorithm used for the financial exigency problem applies to all phases. $\Theta_{\max}$ is determined from initial runs of the BMS or may be set to an arbitrarily large number. Using parametric programming, the entire continuum is spanned. For any given level of Θ, there is a total first-year BMS budget, $B_{\Theta}^{\mathrm{tot}}$ that is calculated as follows:

$$B_{\Theta}^{\mathrm{tot}} = \sum_{s} E_{\Theta}^{1}(s) \quad (5)$$

The only difference between the three phases is in the second-year performance goals as described earlier. All three phases use the following algorithm to find the optimal solution (Θ_{opt}, $B_{\Theta_{\mathrm{opt}}}^{\mathrm{tot}}$):

For $\Theta = 0$ to $\Theta_{\max}$, compute $B_{\Theta}^{\mathrm{tot}}$. If $B_{\Theta}^{\mathrm{tot}} \le \beta^1$ (available first-year network budget), output $\Theta_{\mathrm{opt}} = \Theta$, $B_{\Theta_{\mathrm{opt}}}^{\mathrm{tot}} = B_{\Theta}^{\mathrm{tot}}$. This is the optimal solution. Stop.

It is possible that $B_{\Theta_{\max}}^{\mathrm{tot}}$ may not satisfy the desired first-year budget constrain for Phase A. In this case, Phase B changes the second-year performance goals to match the desirable and undesirable proportions in the current survey. Thus, instead of endeavoring to improve the second-year performance as it is anticipated will be the case for the multiyear model (and Phase A), the stratum desirable and undesirable percentage goals are set to maintain the existing stratum conditions. Then the preceding algorithm is used to search for an optimal solution to this modified set of Year 2 goals for Phase B.

If Phase B cannot find a solution that meets the available budget, then more drastic measures are necessary. Phase C completely removes the Year 2 goals and will spend as much money as possible while still meeting the first-year budget. In Phase C, the first-year M&R scope costs vary from inexpensive [start with $\alpha_{\min} C_{ia}(s)$] to more expensive [$\alpha_{\max} C_{ia}(s)$]. At the low end of this range, the first-year expenditures will be high because of the apparent inexpensive M&R scope costs. As α increases, the first-year expenditures will decrease until finally the budget goal is met. Top management will have to examine the resulting performance and decide if additional funds should be requested.

Figure 5 is the data flow diagram for the financial exigency model. The open-ended boxes are data base tables from the ORACLE relational data base that ties the entire highway maintenance management system (HMMS) together. The HMMS consists of a bridges and structures management system (B&SMS), of which this BMS is a part, linked not only

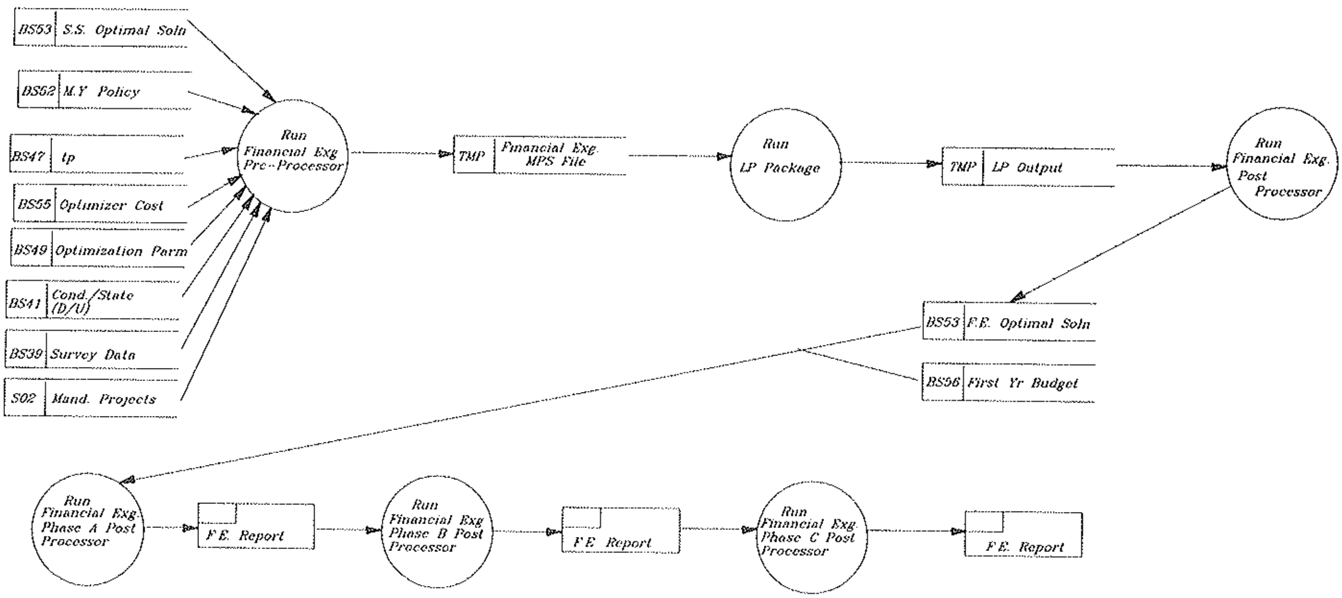

FIGURE 5 Data flow diagram for financial exigency model.

to pavement but also to nonpavement management systems. It is an integrated system that allows the optimal allocation of resources across the entire network of highways, bridges, culverts, tunnels, and all related nonpavement elements. The circles represent the processes that are part of the financial exigency model, and the closed rectangles represent various outputs. A complete description of this data flow diagram was provided by Harper et al. (*5*).

The left hand side of the data flow diagram in Figure 5 shows the following major inputs to the financial exigency preprocessor:

1. Steady-State Optimal Solution—provides the target for the final year of the financial exigency model.
2. Multiyear Policy—provides the yearly desirable and undesirable goals.
3. Transition Probabilities—provide the degradation estimates.
4. M&R Scope Costs (Optimizer Cost)—provide the scope costs as a function of the current condition state.
5. Optimization Tolerance Parameters—provide the tolerances on how closely the steady state solution must be met at the end of the planning horizon.

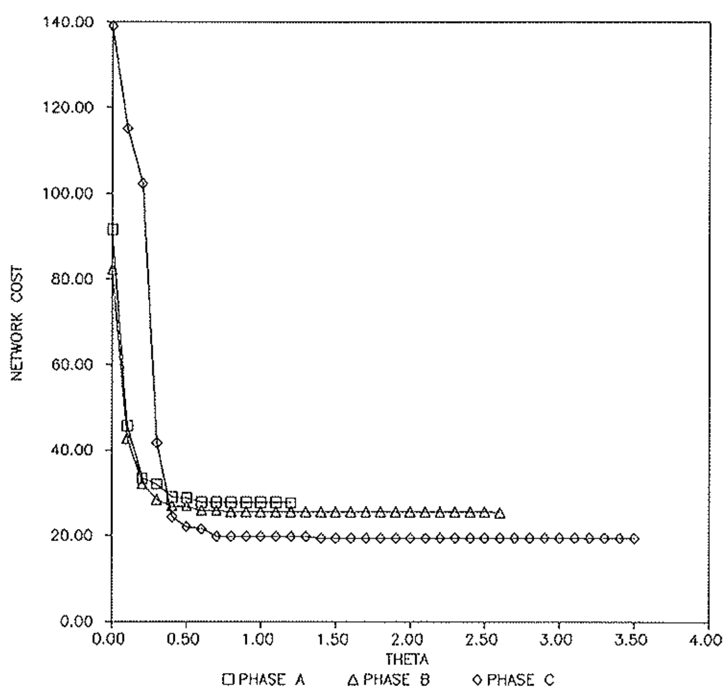

FIGURE 6 Network cost versus Θ.

6. Desirable/Undesirable Condition State—defines each condition state as desirable, undesirable, or neither.
7. Survey Data—provides the first-year boundary conditions giving the proportions of the stratum that are in the various condition states.
8. Mandatory Projects—these projects must be implemented and are not subject to change by the optimization.

The inputs are used to create temporary input files in the MPS program by the financial exigency preprocessor. The MPS files are input to the commercial linear programming (LP) package that produces a temporary output file. The postprocessor uses the LP output to generate the various optimal solutions that will be examined in Phases A, B, and C of the financial exigency model. The first-year budget constraint is used to select the solution set across all strata that meets the available budget. Each phase of the financial exigency model produces a report that indicates how the network budgetary needs change as a function of Θ.

Figure 6 shows example results for Phases A, B, and C. As the Lagrange multiplier increases, the network cost decreases rapidly. It is highly probable that Phase A will be the only financial exigency phase needed to find a network budget that satisfies the available first-year budget. If Phase A cannot reduce the network budgetary needs enough, then Phases B and C may be used to find the optimal solution that will meet the available budget.

CONCLUSION

A BMS was described that integrates separate strata into an overall network optimal solution. Similar techniques are used to link the BMS both with pavement and nonpavement management systems. The use of Lagrange methods and parametric programming allows an efficient solution to the multistrata Markov decision process.

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