Multiperiod Network Improvement Model

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As traffic demand increases over time, improvements to existing transportation networks must be considered for enhancing efficiency, capacity, or both. Because of limited resources even justifiable projects may have to be implemented gradually. The selection and timing of improvement projects are very important to ensure the most cost-effective investment plan. Conducting this task for transportation networks is particularly challenging since the project effects tend to be inherently interdependent. By inadequately estimating project impacts during intermediate periods most existing methods tend to generate inappropriate improvement plans. The study developed a multiperiod network design problem model for the dynamic investment problem. A branch-and-bound algorithm was designed to determine the best project combinations and schedules. An artificial neural network model was used for estimating multiperiod user costs. The proposed model can efficiently handle the interdependencies among projects and demand changes in each period. This method can be used for programming various transportation network improvements or transformations.

Investing in transportation systems to accommodate the increasing demand over time is one of the major issues for public agencies. Because of resource and other physical limitations, selecting the optimal project combination and implementation timing is very important for such programs. This problem is particularly challenging since most network projects are highly interdependent.

Evaluating the interrelations among projects of interest is often a critical issue for investment decisions. Several researchers have sought to derive appropriate expressions for various interrelations among projects. However their efforts have not yielded significant breakthroughs. Neither of these results is satisfactory in transportation networks where projects tend to affect each other. The network effects that cause such interrelations cannot be examined by simple analytical models. Therefore the interdependent terms will not be estimated for any project combinations in this paper. Instead the differences between various aggregate effects will be computed and used for comparing the effectiveness of various project combinations.

Existing methods tend to ignore the intermediate period conditions and hence may lead to inappropriate solutions. Since traffic demand may not increase smoothly over time and throughout the entire network, we should consider the effects of demand changes on networkwide operations. Even when the demand increases smoothly the resulting network equilibrium could be significantly different in each period because of motorist route choice behavior and the changing set of projects already implemented. Hence explicit consideration of intermediate-period conditions is essential in economic evaluations.

It may be realized through the above discussions that the most suitable timing of various improvements is really dependent on many factors. Therefore a model for the multiperiod network design problem (MPNDP) is developed for programming transportation network improvements. This model includes the desirable features of simultaneously determining the best combination of projects and schedules.

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LITERATURE REVIEW

Although a number of project selection studies have been made it seems that relatively little effort has been devoted to assessing interactions among projects (*1*). Researchers typically deal with simple interrelations [e.g., see the papers by Fox et al. (*2*) and Gomes (*3*)] or assume that such information is exogenously provided [e.g., see the paper by Carraway and Schmidt (*4*)].

Hall and Nauda (*1*) provided a taxonomy that characterizes various approaches to research and development project selection. A common situation is that such methods generate a preferred subset of projects without considering implementation timing.

The problem of sequencing capacity expansion projects (SCEPs) is one of the most widely studied in the project sequencing literature (*5,6*). It is quantitatively based, requires specific information on demand, and yields decisions on the preferred projects and the corresponding sequence and timing. However SCEP and most other sequencing models cannot efficiently handle highly interdependent network effects.

The network design problem (NDP) approach has been applied to many network-related problems [e.g., see the papers by LeBlanc (*7*), Magnanti and Wong (*8*), and Janson et al. (*9*)]. The NDP model can consider the systemwide interactions among design decisions and analyze how design decisions affect the operations of a transportation network. However most existing NDP models are useful only for one-period decision making (i.e., project selection). The time dimension must be added to make NDP models suitable for project scheduling.

Akileswaran et al. (*10*) and Johnson et al. (*11*) have shown that SCEP and NDP models are fairly complex. Hence many researchers have used various heuristic solution methods [e.g., Poorzahedy and Turnquist (*12*)]. The most common difficulty encountered in any model is evaluation of network performance with respect to various changes. For a transportation network the traffic assignment model is frequently used to estimate the resulting total travel time. The computation time is quite large even for a network of moderate size.

The artificial neural network (ANN) has been studied as an alternative method for evaluating static network effects (*13*). When a time dimension is incorporated the ANN is shown to be an efficient prediction model for generating the multiperiod total travel times for any network changes (*14*). However it seems that applications of ANNs to transportation problems are just beginning (*15*). To date ANN research or practical applications in trans-

portation engineering are still rare, although they are increasingly popular.

MPNDP MODEL

Given a transportation network and a set of improvement projects we try to find the optimal combination and schedule of projects that minimize the total discounted cost subject to relevant constraints. This is an MPNDP. We consider a planning horizon consisting of several equal discrete time periods (e.g., 1 year) and currently focus on capacity expansion of links (i.e., adding or improving a link).

The MPNDP model has the following features:

1. Both user and incremental supplier costs are considered in the objective function,
2. Periodic budgets are the only resource for construction, and the unspent portion may be rolled over into succeeding periods,
3. Project continuity is preserved, and
4. The resulting capacity changes in each period are specifically considered.

It is assumed that uncertainties about traffic demands and project costs may be disregarded (*8*). Only incremental supplier costs with respect to the null (i.e., existing) network will be counted. In this paper the projects are treated as immediately available to motorists in the first periods they are implemented. Another model considering project construction and possible traffic disruption has been proposed elsewhere (*16*). The solution framework discussed in the next section may be employed with a slightly different interpretation. However the computational burden would increase.

The following notation is used to present a mathematical formulation of the MPNDP model:

A = set of links;
B_h = budget for projects in period $\boldsymbol{h}$;
C_{ah} = project cost of link $\boldsymbol{a}$ in period $\boldsymbol{h}$, $\boldsymbol{a} \in P$;
$CRF_{r\tau}$ = capital recovery factor for discount rate r and τ periods;
H = planning horizon;
K_a = initial capacity of link $\boldsymbol{a}$, $\boldsymbol{a} \in$ A;
K_{ah} = capacity of link $\boldsymbol{a}$ in period $\boldsymbol{h}$, $\boldsymbol{a} \in$ A;
MAN_{ah} = maintenance cost of link $\boldsymbol{a}$ in period $\boldsymbol{h}$, $\boldsymbol{a} \in$ P;
N = set of nodes;
P (P') = set of links with (without) projects, P' = A − P;
PVF_{rh} = present value factor for discount rate r in period $\boldsymbol{h}$;
S_h = unspent budget in period $\boldsymbol{h}$; $S_0 = 0$;
X = flow patterns on each link, = (X_{ah}) for $\boldsymbol{a} \in$ A and $\boldsymbol{h} \in H$;
r = discount rate;
x_{ah} = flow assigned on link $\boldsymbol{a}$ in period $\boldsymbol{h}$; $\boldsymbol{a} \in$ A and $\boldsymbol{h} \in H$;
α_a, β_a = parameters of the travel time function on link $\boldsymbol{a}$, $\boldsymbol{a} \in$ A;
ΔK_a = proposed additional capacity on link $\boldsymbol{a}$, $\boldsymbol{a} \in$ P;
Ψ = unit cost of user travel time;
μ_a = travel time at zero flow on link $\boldsymbol{a}$, $\boldsymbol{a} \in$ A; and
π_a = capital cost of link $\boldsymbol{a}$, $\boldsymbol{a} \in$ P.

Assume m projects and τ periods are considered. Let V equal v_{ah} be the $m \times \tau$ decision matrix for $\boldsymbol{a} = 1, \ldots, m$, and $\boldsymbol{h} = 1, \ldots, \tau$. Each element in V is defined as follows:

$$v_{ah} = \begin{cases} 1 & \text{if project on link } \boldsymbol{a} \text{ is in service in period } \boldsymbol{h} \\ 0 & \text{otherwise} \end{cases}$$

Each matrix V represents a particular investment plan that specifies the preferred projects and implementation times. To preserve project continuity we require

$$v_{ah} \leq v_{a,h+1} \qquad \forall\, \boldsymbol{a} \in P, \boldsymbol{h} \in H \tag{1}$$

For example if link $\boldsymbol{a}$ is to be improved in period 3, then the corresponding solution for link $\boldsymbol{a}$ would be $v_{a1} = v_{a2} = 0$ and $v_{a3} = v_{a4} = \ldots = v_{a\tau} = 1$. By thus defining decision variables capacity changes in each time period can be properly incorporated. Hence the corresponding average travel times can be accurately computed for the improved links. This new idea is presented here to reflect the effects of each improvement project.

The average travel time on link $\boldsymbol{a}$ in period $\boldsymbol{h}$ depends on project implementation and equilibrium flow. It is computed by

$$t_{ah}(x_{ah}, v_{ah}) = \mu_a[1 + \alpha_a(x_{ah}/K_{ah})^{\beta_a}] \tag{2}$$

where

$$K_{ah} = K_a + v_{ah}\Delta K_a \qquad \forall\, \boldsymbol{a} \in P, \boldsymbol{h} \in H \tag{3}$$

$$K_{ah} = K_a \qquad \forall\, \boldsymbol{a} \in P', \boldsymbol{h} \in H \tag{4}$$

By setting suitable initial link capacities both the link-adding and link-improving options can be handled simply by Equation 3. The initial capacity K_a may be assumed to be arbitrarily small for any possible new link, so that one unit flow will result in an extremely long travel time on this link. Therefore no traffic will be assigned to a yet nonexistent link. For existing links K_a is equal to its current physical capacity. Once this link is added or improved the second term on the right-hand side will ensure the addition of new capacity to the network. Then appropriate traffic volumes may be assigned accordingly.

The periodic project cost on link $\boldsymbol{a}$ is computed by converting the capital cost to a periodic expenditure plus a maintenance cost in each period. Hence,

$$C_{ah} = \pi_a CRF_{r\tau} + MAN_{ah}PVF_{rh} \qquad \forall\, \boldsymbol{a} \in P, \boldsymbol{h} \in H \tag{5}$$

where

$$CRF_{r\tau} = \frac{r(1 + r)^\tau}{(1 + r)^\tau - 1} \tag{6}$$

$$PVF_{rh} = 1/(1 + r)^h \tag{7}$$

In principle the periodic maintenance cost may depend on the age or utilization rate of the facility as discussed by Markow (*17*) and Fwa et al. (*18*). However practically reliable results are still underdeveloped (*19*). Hence MAN_{ah} is assumed to be a fixed fraction of the project capital cost in the present study.

The system cost is defined for each period as the sum of user travel time costs and project costs:

$$\text{System cost in period } \boldsymbol{h} = \sum_{a \in A} [\Psi x_{ah} t_{ah}(x_{ah}, v_{ah}) + v_{ah}C_{ah}] \tag{8}$$

It is clear that the system cost depends not only on the project implementation decisions but also on the traffic flows on each link. Furthermore the flow patterns will be updated according to the projects selected up to the current period. There seems to exist a hierarchy for this problem. A higher-level position for the decisions on projects seems appropriate. Given the decision variables v_{ah} the equilibrium flow assignment may be processed at the lower level. Consequently MPNDP is expressed by two subproblems at different levels.

We now define the solution set Ω for MPNDP as

$$\Omega = \{V_i = (v_{ah}) | v_{ah} = 0 \text{ or } 1,\ i = 1, 2, \ldots, (\tau + 1)^m\} \tag{9}$$

A total number of $(\tau + 1)^m$ possible solutions is included in Ω for the corresponding MPNDP.

The MPNDP consists of two parts, namely the network priority program problem (NPPP) in the upper level and the periodic network equilibrium problem (PNEP) in the lower level. The NPPP is formulated below as a nonlinear mixed-integer program subject to constraints representing periodic funds available and project continuity. The NPPP formulation is:

$$\underset{V \in \Omega}{\text{Minimize}}\ Z = \sum_{h \in H} \sum_{a \in A} [\Psi T_{ah}(x^*_{ah}, v_{ah}) + v_{ah} C_{ah}] \tag{10}$$

subject to

$$\sum_{a \in P} (v_{ah} - v_{a,h-1}) \pi_a / PVF_{r,h-1} + S_h - S_{h-1}/PVF_{r,1} = B_h \qquad \forall\ \boldsymbol{h} \in H \tag{11}$$

$$S_h \geq 0 \qquad \forall\ \boldsymbol{h} \in H \tag{12}$$

$$v_{a,h-1} \leq v_{ah} \qquad \forall\ \boldsymbol{a} \in P, \boldsymbol{h} \in H \tag{13}$$

$$v_{ah} = 0 \text{ or } 1 \qquad \forall\ \boldsymbol{a} \in P, \boldsymbol{h} \in H \tag{14}$$

In Equation 10 x^*_{ah} is the optimal solution of the following network equilibrium problem in period $\boldsymbol{h}$ for any given feasible decision matrix V.

The PNEP formulation is:

$$\underset{X}{\text{Minimize}}\ Z' = \sum_{a \in A} \int_0^{x_{ah}} t_{ah}(u, v_{ah}) du \tag{15}$$

subject to

$$\sum_{k \in K_{rsh}} f^{rs}_{kh} = q_{rsh} \qquad \forall\ r, s \in R_h \tag{16}$$

$$x_{ah} = \sum_{r,s \in R_h} \sum_{k \in K_{rsh}} f^{rs}_{kh} \delta^{rs}_{akh} \qquad \forall\ \boldsymbol{a} \in A \tag{17}$$

$$f^{rs}_{kh} \geq 0 \qquad \forall\ k \in K_{rsh}, r, s \in R_h \tag{18}$$

where

K_{rsh} = set of paths connecting origin-destination (O-D) pair r-s in period $\boldsymbol{h}$, for $r,s \in R_h$;
R_h = set of origins and destinations in period $\boldsymbol{h}$, $R_h \subseteq$ N;
f^{rs}_{kh} = flow on path k connecting O-D pair r-s in period $\boldsymbol{h}$;
q_{rsh} = trip rate between O-D pair r-s in period $\boldsymbol{h}$; and
δ^{rs}_{akh} = 1 if link $\boldsymbol{a}$ is on path k between O-D pair r-s in period $\boldsymbol{h}$ and 0 otherwise.

The bilevel structure of the MPNDP model is similar to those presented by LeBlanc and Boyce (*20*) and Bard (*21*). However the proposed model is more realistic since the improvements are considered for the different demands and corresponding user behaviors in each period throughout the planning horizon. On the other hand this model is considerably more difficult to solve because of the extensive and complex interactions between users and planners.

SOLUTION METHOD

Considering the project continuity constraint there are only $\tau + 1$ possible decisions for each row (i.e., for each individual project) in the decision matrix. These cases may be represented by summing up the values of decision variables in the same row. Hence only a row sum variable v_a is needed for any possible implementation of project $\boldsymbol{a}$. Consequently the row sum vector may be appropriately constructed with the following definition to replace the decision matrix V:

$$RS = (v_1, v_2, \ldots, v_m)^T \tag{19}$$

$$v_a = \tau + 1 - \sum_{h=1}^{\tau} v_{ah} \qquad \forall\ \boldsymbol{a} \in P \tag{20}$$

In Equation 19 T stands for the transpose of a vector.

The row sum variable is a convenient representation since each value corresponds to a decision on project selection and scheduling. Then we may modify Equation 9 as

$$\Omega = \{RS_i | i = 1, 2, \ldots, (\tau + 1)^m\} \tag{21}$$

Note that with Equations 19 through 21 all elements in the set Ω already implicitly fulfill the project continuity constraint. Hence only the budget constraint remains to be satisfied in the solution procedure.

It has been shown that an efficient project sequence is quite helpful in the solution process [e.g., Erlenkotter (*22*), Janson and Husaini (*23*), and Martinelli (*24*)]. It is usually obtained by ranking the relative effects of projects on the system. A good initial project sequence can speed up the proposed solution method. The initialization criterion used here is the saving/cost ratio of each individual project.

To solve the MPNDP a branch-and-bound (BB) procedure along with an ANN model is developed. The proposed procedure can cost-effectively evaluate the resulting system cost for each solution considered and screen inferior solutions to quickly obtain the optimal solution.

ANN Model

The motivation and justification of using the ANN approach is its small predictive error as well as its reasonable computational bur-

den. In particular when only the total travel time in a transportation network is needed a relatively simple ANN model may serve as a proxy for the conventional traffic assignment model (*14*). However several specific choices must be made for the training parameters.

The ANN model is constructed to compute the system equilibrium (SE) user travel times, taking into consideration the effects of project selection, scheduling, and different demands over time. The desirable feature of the ANN approach is that, after the ANN is trained, it may be repeatedly used for any analysis on the MPNDP, in which each replication requires very little computation time. The ANN approach is especially suitable for relatively large transportation networks in which long computation times are usually required for traffic assignments. Some relevant discussion and validation are provided by Wei (*16*).

BB Procedure

Considering various factors in the transportation network improvement problem, a preliminary conclusion is that lower total system costs tend to be associated with the earlier implementation of projects. Hence the objective function of NPPP is roughly a U-shaped curve skewing to smaller values of row sum variables. This property is particularly important on capacitated networks where congestion effects increase user travel time exponentially. The proposed BB method is mainly based on this observation, and detailed discussions may be found in Wei (*16*).

With the initial project sequence a synthesized branch rule is developed and the ANN model is activated whenever a lower bound (LB) is needed in the solution process. The conventional traffic assignment is used to estimate the user equilibrium (UE) user travel times for each complete solution. On the basis of the branch rule the proposed BB method would generate a tree with as many levels as the number of row sum variables (i.e., number of projects). Hence the level index L is also used as the project index.

To monitor the progress of the BB method a list containing the branch indexes in descending order is needed. Information about the new branch is added to the top of the branch index list. Each branch index is associated with a partial solution or a complete solution when the level index is equal to m. In any case the branch with the largest index is at the top of the list and will be processed first. As a general rule the indexes of branches from the same predecessor should be labeled in the reverse order of the assigned values for the variables under current consideration. The branch index and associated information will be removed from the list after further partitioning or fathoming is accomplished.

The core of the proposed BB method is to choose the best possible solution (BPS) for each branch, given the decision on already specified projects. Since each branch represents a number of possible solutions, the intelligently derived BPS would sufficiently reflect the goodness of the associated solutions. Such a task is accomplished by estimating and updating the earliest implementation times (EITs) of all unspecified projects.

The EIT of project $\boldsymbol{a}$, h_a, is the smallest time index in which project $\boldsymbol{a}$ may be implemented without violating the relevant constraints as well as the schedule of already specified projects. For each partial solution updating of EITs is equivalent to choosing the smallest values for free row sum variables according to the fixed values of other variables. The proposed procedure is described below.

At level 0 (i.e., root of the BB tree) the EITs of all projects are verified by

$$\boldsymbol{h}'_a = \min\left\{ j \,\middle|\, \sum_{h=1}^{j} B_h PVF_{r,h-1} \geq \pi_a \right\} \qquad \forall\, \boldsymbol{a} \in P \tag{22}$$

For partial solutions at level $L > 0$ the first L projects have been specified to have fixed values. The remaining m-L variables are free, and their updated EITs corresponding to those fixed variables must be decided. The largest value among the already specified variables is identified by

$$v'_L = \begin{cases} \max\{v_i | i \leq L\} & \text{if some } v_i \leq \tau \\ 0 & \text{otherwise} \end{cases} \tag{23}$$

v'_L indicates the last period for accumulating available budget. When v'_L is zero the projects specified so far are not to be implemented and the budget is not used at all. Thus the EITs of the free variables are set equal to $\boldsymbol{h}'_a$, obtained in Equation 22. For nonzero v'_L the remaining budget is then obtained by subtracting the construction costs of the already implemented projects.

The appropriate EITs for free variables are determined by one of the following conditions:

1. If the remaining budget is larger than any construction cost of the free projects, the prevailing unspecified projects may be also implemented before period v'_L without exceeding the budget limit. Thus when Equation 24 holds for any free project the corresponding EIT is set equal to the EIT obtained in its predecessor node.

$$\sum_{h=1}^{v'_L} B_h PVF_{r,h-1} - \sum_{a=1}^{L} \pi_a \geq \pi_i \qquad L < i \leq m \tag{24}$$

2. Otherwise the EIT of free project i is obtained by

$$\boldsymbol{h}_i = \min\left\{ j \,\middle|\, \sum_{h=1}^{j} B_h PVF_{r,h-1} - \sum_{a=1}^{L} \pi_a \geq \pi_i \right\} \qquad L < i \leq m \tag{25}$$

Note that the EIT of each unspecified project obtained is thus based on the budget relaxation proposed by Wei (*16*). This is to ensure the feasibility of already chosen projects and the achievement of lower costs from all unselected projects. Thus the greatest contribution that each project may yield to the system is obtained on the basis of the currently established network. Such budget relaxation is also desirable to reduce the problem complexity since the not yet considered projects will compete for the remaining budget. As a result the complete solutions in the BB tree are always budget feasible.

With the above treatments new branches can be created rapidly and more partial solutions can be examined for their system effectiveness. Since the ANN model is fairly efficient the lower bound is quite tight and the overall solution process is very fast.

Algorithmic Procedures

The complete solution algorithm for the MPNDP is condensed as follows:

Step 0: *Preprocess.* Presort projects according to their relative system effectiveness and assign the project index in that order.

Step 1: *ANN Training.* Train the ANN by using the methods discussed by Wei (*16*).

Step 2: *Initialization.*
- a. Set L equal to 0.
- b. Compute initial upper bound (UB) equal to Z_{UE} under the current network configuration.
- c. Compute the EITs at level L for all projects by using Equation 22.

Step 3: *Branching.*
- a. Set L equal to $L + 1$.
- b. First, for $L < m$ partition v_L according to the updated EIT, assign branch indexes, generate partial solutions, and put this information on the branch index list. Second, for L equal to m partition v_m according to the updated EIT, assign branch indexes, generate complete solutions, and put this information on the branch index list.

Step 4: *Bound Computation.*
- a. Pick the first branch and the associated partial solution from the list revised in Step 3.
- b. If L is equal to m go to Task A. Otherwise obtain the updated EITs for free variables by using Equation 24 or 25, estimate the SE total travel time for the corresponding BPS with the trained ANN, and compute the LB.

Step 5: *Comparison.*
- a. For LB greater than or equal to UB fathom this solution and go to Task B.
- b. For LB less than UB go to Step 3 if L is less than m; otherwise store this incumbent solution, set UB equal to LB, and go to Task B.

Task A: *Computing Z_{UE} for Complete Solutions.* For the complete solution perform UE traffic assignment and compute Z_{UE} under the current project schedule. Set LB equal to Z_{UE} and go to Step 5.

Task B: *Checking the Branch Index List*
- a. For L equal to 1:
  - If there is no branch at the same level, stop the BB process; the latest incumbent solution is the optimal solution.
  - Otherwise go to Step 4.
- b. For L greater than 1:
  - If there is no branch at level L go to level $L - 1$. If there is no branch at level $L - 1$, set L equal to $L - 1$ and go to Task B; otherwise set L equal to $L - 1$ and go to Step 4.
  - Otherwise go to Step 4.

For a three-project, 5-year case discussed by Wei (*16*) the BB solution process is shown in Figure 1. Note that because of the relatively small problem size the total costs of possible solutions are quite close. Hence quite a few complete solutions are evaluated at the lowest level. As shown in the next section the proposed solution method is very efficient and only a few complete solutions need to be evaluated when a practical problem size is considered.

NUMERICAL EXAMPLE

A realistic problem is used in this section for demonstrating the solution method proposed for the MPNDP model. The relevant information was provided by the Maryland State Highway Administration for a related study (*25*). The characteristics of this illustrative problem are practical enough that it can be used to validate the usefulness of the proposed methodology for real-world problems.

To alleviate future congestion in Calvert County, Md., five projects are considered, as shown in Figure 2. Projects X, Y, and Z add one more traffic lane to the associated links in each direction. Alternatively projects P and Q provide bypass routes for most of the congested areas. The bypass routes are assumed to be two-lane, two-way highways.

These five projects, if all are completed, would greatly relieve future traffic congestion. However this is hardly possible because of limited funds. In addition since two parallel routes exist for most of the congested areas the project effects tend to overlap. Hence installing two parallel projects simultaneously is unlikely to be efficient.

Projects are considered for a 12-year planning horizon, from the years 1999 to 2010. All cost and saving computations will be based on the present value in the year 1999. The primary factors used for these computations are listed in Table 1. According to Equation 21 there are 13^5 (371,293) possible combinations of projects and schedules to be evaluated, which is not a trivial task.

To set up an MPNDP for this case a number of preliminary analyses are conducted. Without improvements it is found that the overall average speed is reduced from 38.25 mph in the year 1999 to 20.86 mph in the year 2010. Hence significant improvements on this highway system are desirable to preserve a reasonable level of service. The effects and capital costs of each individual project are listed in Table 2. The last column in Table 2 shows the cost-effectiveness rank of each individual project and constitutes the solution of many scheduling methods.

Table 2 also provides some information about project combinations. In particular the total user travel time is almost halved and the average travel speed is almost preserved at the year 1999 level if all projects are implemented. Nevertheless the corresponding travel time savings are notably less than the sum of individual ones. This explicitly indicates the interdependencies among various projects.

According to the factors listed in Table 1 the total cost of the null system is $2,371 million. Assuming that the available budget is $15 million/year, this test problem is solved with a trained ANN and the proposed BB method. The solution process takes only a few seconds of central processing unit time on a 486-based personal computer. The optimal scheduling solution for (P, X, Y, Z, Q) is (3, 11, 5, 5, 13), with a total cost $1,743 million. The costly project Q is not considered for implementation, although its time savings is among the highest. The system cost savings that would result from this implementation plan are $628 million (or 26 percent of the null alternative) for the 12-year planning horizon.

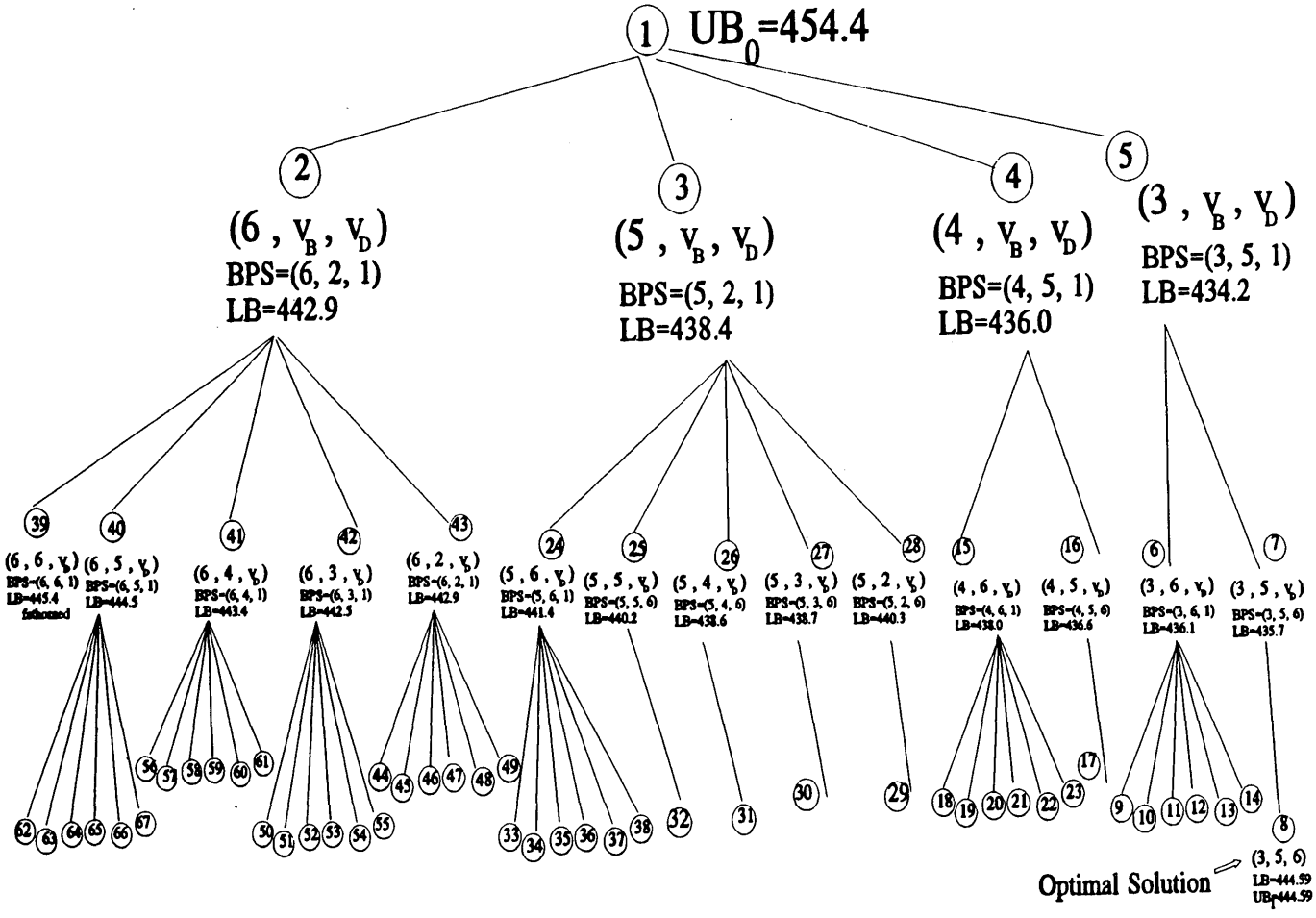

FIGURE 1 Illustration of proposed BB method.

It is helpful to justify the usefulness of the proposed methodology by comparing its results with those of the scheduling decision obtained on the basis of independent project effects. The approach is to use the independent sequence shown in Table 2 and to determine the project implementation times that lead to the minimum total cost. Given the same conditions discussed above the optimal scheduling solution is (3, 4, 7, 11, 13) and has a total cost $1,841 million. It is clear that a better solution, with $98 million of additional savings, is found by considering project interdependencies.

The effects of various budget levels are analyzed. The approach is to restrict the annual budget so that the present value of total budgets is a certain fraction of the total project costs. Six budget levels, from 50 to 100 percent of total project costs, are considered, and the results are shown in Table 3. It is interesting to note that optimal solutions for different budget levels yield similar improvement effects over the null system, as shown in the last column of Table 3. However the optimal scheduling solutions and the corresponding total system costs are quite different.

It is found that for lower budget levels (e.g., 50 and 60 percent) improvements on existing links are preferred since the associated costs are usually lower. The new bypass routes are either deferred or not considered for installation. If, however, the budget is insufficient (e.g., 70 percent or higher) new links may be added in the early stages.

Table 3 also provides information on the processes of the proposed BB method, that is, the numbers of nodes created and the numbers of feasible solutions evaluated. Since the nodes represent both partial and complete solutions generated throughout the solution procedure, this information indicates that the proposed BB method is fairly effective. The infeasible or inferior solutions are screened out efficiently because of the specially designed branching and bounding rules. Only a small fraction of possible solutions must be evaluated. This demonstrates the highly desirable property addressed in the previous section. Additionally the information about BB nodes seems to indicate that the proposed method is best suited for budget levels of between 80 and 100 percent of total project costs.

POTENTIAL APPLICATIONS

The MPNDP model and solution method proposed in this paper is especially designed for prioritizing interrelated projects in trans-

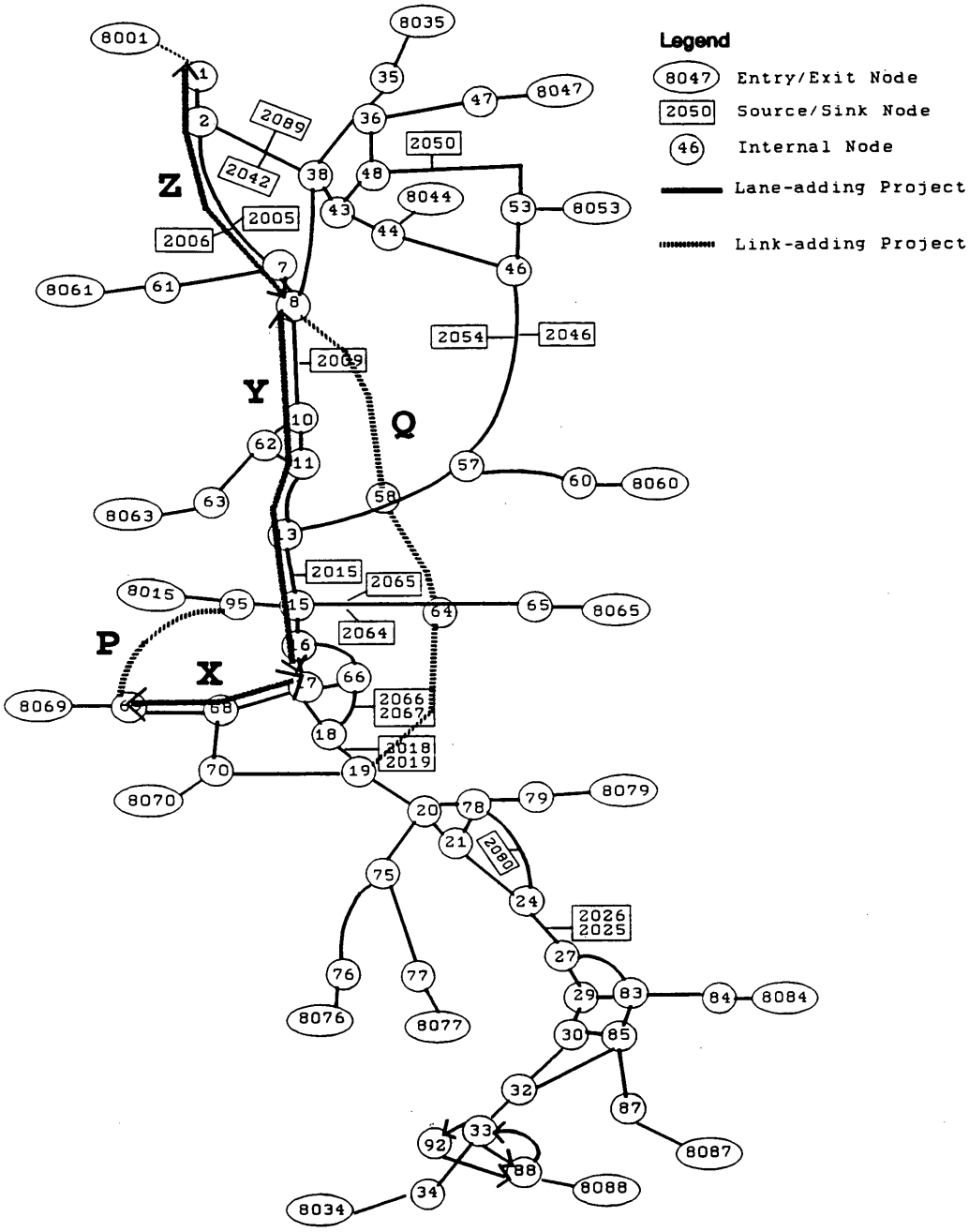

FIGURE 2 Proposed projects for Calvert County, Md., by year 2010.

portation networks. Below several potential applications of the proposed MPNDP model are discussed.

Application in Highway Maintenance Planning

Conventional highway maintenance planning tends to neglect the impacts on roadway users (*19*). Hence the resulting maintenance plan is rarely the best conceivable. The combined costs of highway maintenance and traffic operations must be considered for proper maintenance planning. In particular when major rehabilitation is undertaken the influence on existing traffic patterns is fairly significant.

Various maintenance alternatives may be treated as possible projects that recover the network performance to different levels. Then the traffic assignment model may be used to estimate the aggregate utilization of the roadway system. Consequently the mutual influences between the user and the facility can be properly

TABLE 1 Parameters Used for Methodology Demonstration

Item	Value
Unit Value of Time ($/Veh-hour)	10.0
Peak Hour to Day Ratio	0.15
Day to Year Ratio	1/300
Planning Horizon (Years)	12
Interest Rate (%)	6
New Construction Cost (Million $/Lane mile)	4.5
Roadway Widening Cost (Million $/Lane mile)	3.0
Ratio of Overhead and Other Costs to Construction Cost (%)	20
Annual Maintenance to Construction Cost Ratio (%)	1.55

TABLE 2 Project Effects and Ranking in Year 2010

Project	Length miles	Project Cost[1](A)	Total UTT[2]	Speed[3] MPH	UTT Saving(B)	B/A Ratio
Null	-	-	15500	20.86	-	-
P	5.40	29.2	12242	26.32	3258	112
X	5.98	21.5	13621	23.69	1879	87
Y	10.27	37.0	12359	26.07	3141	85
Z	8.38	30.2	13937	23.26	1563	52
Q	12.88	69.6	12351	26.02	3149	45
Combination						
XYZ	24.63	88.7	9000	35.73	6500	73
PQ	18.28	98.8	10956	28.99	4544	46
ALL	42.91	187.5	8521	36.82	6979	37

[1]Million dollars
[2]User equilibrium travel time, veh-hours/peak-hour
[3]Average peak hour speed at network level, miles/hour

taken into account. For example the actual deterioration would depend on route selection by drivers, which in turn affects maintenance needs.

HOV Lanes and IVHS Applications

The proposed MPNDP can be applied to evaluate various traffic improvement plans. For example it can be used for determining the suitable stages for introducing high-occupancy-vehicle (HOV) lanes in different locations. With small additional efforts the proposed methodology may also be used to plan advanced transportation systems, for example, intelligent vehicle-highway systems (IVHSs).

A critical issue in these applications is assessment of the traffic pattern changes owing to HOV lanes or various IVHS technologies. In particular only a fraction of conventional users and facilities will be affected. Special traffic assignment models are thus needed to deal with vehicles with various occupancies or equipment.

With such information proper samples for ANN training can be generated according to the plans under consideration. Then the MPNDP for implementing HOV lanes or IVHS technologies within a certain horizon can be formulated and solved by the proposed BB method.

CONCLUSIONS

Selecting the optimal project combination and implementation timing is very important for transportation systems. This problem tends to be fairly difficult since complex project interrelations often exist. The main drawbacks of most existing methods are long computation times and neglect of conditions in the intermediate period. The latter may lead to inappropriate solutions. A model for multiperiod transportation network priority programming was developed in the study described here. This model has the desirable features of simultaneously determining the best combination of projects and schedules. The proposed model is more realistic than others since the improvements are considered for the different demands and corresponding user behaviors in each time period throughout the planning horizon.

To solve the MPNDP a BB procedure is specifically designed. The ANN approach is adapted to compute the resulting user travel times, taking into consideration the effects of project selection, scheduling, and different demands over time. The overall solution method can evaluate possible solutions very cost-effectively and can screen out many inferior solutions to save computational efforts. The numerical examples show that only a small fraction of possible solutions must be evaluated and the proposed BB method seems to be especially fast for budget levels of between 80 and 100 percent of total project costs.

The MPNDP model may be considered for many other network-related problems in which interrelated projects must be scheduled.

TABLE 3 Results for Various Budget Levels

Budget Level[1]	Annual Budget	BB Nodes[2]	# Feasible Solutions	Optimal Solution	Total Cost	Improvement Over Null[3]
50%	10.5	463	9	(11,3,4,13,13)	1722	27%
60%	12.5	565	7	(10,2,4,13,13)	1687	29%
70%	15.0	120	4	(3,11,5,5,13)	1743	26%
80%	17.0	75	3	(8,2,3,9,13)	1726	27%
90%	19.0	49	2	(2,3,8,5,13)	1729	27%
100%	21.1	42	2	(2,3,5,7,13)	1747	26%

[1]Total project cost = 187.5
[2]Nodes created in the branch-and-bound solution process
[3]Total cost of null alternative = 2371

Several conceivable extensions of the proposed methodology are worth pursuing, for example, highway maintenance planning, suitable stages for HOV lanes in different locations, and the transition timing of various IVHS technologies.

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