Programming Route Improvements to the National Highway Network

BRUCE N. JANSON, L. SCOTT BUCKELS, AND BRUCE E. PETERSON

A network design approach to the selection and programming of strategic route improvements to the U.S. national highway network of Interstates, four-lane urban highways, and rural principal arterials is described. Alternative route improvement strategies are defined as mutually exclusive sets of link improvements that can be programmed for construction within any decade of a multidecade planning horizon. Two improvement strategies considered for each route are (a) to make every link median divided with controlled access and at least four lanes, or (b) to make every link at least four lanes, but without any changes to median division or access control. Route improvement strategies programmed for each decade are constrained by 10-year funding allocations. A trip distribution model is used to distribute commodity shipments forecasted for each decade among regions. The example evaluates 536 potential improvements to 289 major highway routes between adjacent Bureau of Economic Analysis regions, or nearly two improvement strategies per route. Route improvement benefits are computed as changes in the value of the objective function, which is the total discounted interregional shipment cost for all years of the planning horizon. Because different routes and interregional shipments can share common links, a rank-add-and-swap heuristic solution procedure was developed and applied that accounts for the interdependent costs and benefits of route improvements. Implications of this network design approach for strategic planning of the national highway network are discussed.

A variety of network design models have been developed and applied to discrete decision problems concerning adjustments to facilities or services in network-based systems. Combined models of network design and travel demand forecasting have been described for the planning and evaluation of multimodal regional transportation systems for both person and freight travel. Heuristic solution approaches have been found to obtain good solutions for many applications to the degree of optimality required. Additionally, applications of network design models to transportation have been facilitated in recent years by their integration with geographic information systems and microcomputer data bases.

The problem of planning long-range strategic improvements to competing routes or corridors of an interregional highway network is addressed. A network improvement programming formulation and heuristic solution approach are described in which route improvement strategies are candidates for inclusion in 10-year periods of a 30- to 50-year planning horizon. Alternative investment strategies for each route are specified as mutually exclusive sets of link improvements in successive decades, where each set is treated as a separate project candidate in a project programming framework. The two improvement strategies considered for each route are to make all necessary upgrades so that (a) every link is median divided with controlled access and at least four lanes, or that (b) every link is at least four lanes, but without any changes to median division or access control.

B. N. Janson, Department of Civil Engineering, University of Colorado, Denver, Colo. 80217-3364. L. S. Buckels, Union Camp Corporation, Wayne, N.J. 07470. B. E. Peterson, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tenn. 37831-6206.

In an example application, alternative improvements to 289 major highway routes between adjacent Bureau of Economic Analysis (BEA) regions in the 48 contiguous states of the United States are considered. These routes connect the geographic population centroids (as of 1985) of 181 BEA regions (as defined in 1989), and are composed of Interstates, four-lane urban highways, and rural principal arterials, some of which have only two lanes. Routes without any two-lane links have only one improvement strategy option. One improvement strategy is considered for 42 routes with no two-lane links, and two improvement strategies are considered for the other 247 routes. Each strategy for each route can be programmed in any of three decades (1991 to 2000, 2001 to 2010, and 2010 to 2020), resulting in a total of 1,608 possible route, strategy, and decade combinations. The full network to which these routes belong contains 7,775 bidirectional links and 5,620 nodes.

The benefit of a route improvement at any point in the solution process is its reduction to the total interregional commodity shipment cost for the entire planning horizon, which is the objective function of these problems. The strategy programming criterion is the ratio of objective function reduction per unit of construction cost for a given route improvement, which is an effective gradient measure used in solving zero-one integer programming problems. The total construction cost of route improvements must be feasible within the funds allocated for each decade. All costs and benefits are discounted to present values according to an assumed discount rate to calculate the benefit-cost ratio and budget feasibility of each route improvement strategy.

Two problem formulations are presented for fixed versus variable interregional shipment distributions. The first problem assumes fixed interregional shipment matrices that vary by decade, but not because of network changes. The second problem incorporates a typical trip distribution model to redistribute interregional shipments in each decade on the basis of path cost changes caused by network improvements. Because different routes and interregional shipments can share common links, a rank-add-and-swap heuristic solution procedure was designed to account for the interdependent costs and benefits of alternative route improvements. Optimal and near-optimal solutions to other network design and project programming problems have been obtained by using this same basic heuristic solution approach, even when the number of network improvements made per iteration of the algorithm is increased from one to many. Ways of using this modeling approach for planning future expansions and improvements to the Interstate highway system are discussed.

BACKGROUND

The basic network design problem is to determine a set of link additions or improvements that are feasible within the resource constraints specified so that the performance of the network is improved by the maximum amount. Performance of the network is usually approximated by some system-wide objective function, such as the total travel cost of all person trips or commodity shipments. Link additions usually represent new roads or transit routes, whereas link improvements represent upgrades to existing facilities or services. Service level reductions for some routes can also be evaluated by adding traffic restrictions or reducing transit services. For directed networks in which bidirectional links are coded as directed arc pairs, network changes that only affect one direction of flow can also be evaluated. The example in this paper only considers symmetrical link improvements for both directions of flow.

The unit shipment cost of each link will be assumed to be fixed regardless of flow volume. For networks with fixed-link travel costs, the optimal routing of shipments is by shortest paths. Link flows are determined in the first problem (NIP1) by assigning a fixed region-to-region shipment matrix for each decade to shortest paths of the network with improvements made in the current and previous decades. In the second problem (NIP2), a gravity-type distribution model is used to recalculate an interregional shipment matrix for each decade according to shortest-path costs. Link flows are determined in NIP2 by assigning the variable shipment matrices to the minimum cost routes of each 10-year network plan. The forecasted origin and destination shipment totals for each region in each decade are held fixed in all cases.

Other researchers, such as LeBlanc (*1*), Boyce and Janson (*2*), Poorzahedy and Turnquist (*3*), and LeBlanc and Boyce (*4*), have developed formulations and solution algorithms to network design problems in which travel costs are dependent on link flows. While these formulations are more representative of the supply constraints that affect travel costs on congested networks, they are not generally applicable to interregional network improvement analyses in which congestion is not a major factor. Furthermore, a network design problem in which the objective is to minimize total user cost, but which also assigns traffic to routes on the basis of user equilibrium criteria, may contain several local optima that are inferior to the global optimum. Network design problems with variable costs in which traffic is assigned in a system-optimal manner do not have the same difficulty, but formulations and test problems of that type are not examined in this paper.

Magnanti and Wong (*5*) review several types of network design problems for transportation planning, and they summarize reported experiences with various optimization and heuristic solution techniques. A primary consideration in the development and use of these or any models is the level of effort required for the degree of useful results obtained. Because model results serve as only one factor in the overall decision-making process, a model's development cost and computational burden is often a deterrent to its implementation. Furthermore, many forms of deterministic optimization models are not well suited to the qualitative considerations and quantitative uncertainties inherent in many actual design settings. In situations where knowledge of actual costs and benefits is rather approximate and a clearly dominant design choice is not apparent, a cost-effective procedure must be used to identify good and perhaps near-optimal designs.

Complete enumeration of all feasible and infeasible solutions to a combinatorial problem with N candidate projects would require the evaluation of 2^N solutions. However, the imposition of a single budget constraint greatly reduces the number of feasible solutions that need to be examined. For example, given a funding constraint of F and an average cost $\bar{c}$ for N candidate projects, then a random subset of R projects would have a total cost of about F, where $R = F/\bar{c}$. Because there are $N!/R!(N - R)!$ subsets of N projects containing exactly R projects, this number serves as an approximate upper bound to the number of solutions that any reasonably efficient search process would need to examine in order to obtain optimality. Bounding rules can be incorporated into branch-and-bound procedures, such as those described by Balas (*6*) and Geoffrion (*7,8*) to reduce the number of subsets requiring examination even further without violating optimality. On the other hand, the heuristic solution procedure requires that just kN networks be examined, where k is a constant that can be specified or at least estimated before executing the heuristic, and k never needs to exceed R.

A NETWORK IMPROVEMENT PROBLEM INVOLVING FIXED SHIPMENTS (NIP1)

All commodity shipments will be assumed to originate and terminate at nodal centroids of the 181 BEA regions covering the 48 contiguous states. The first network design problem examined here is one in which shipments between each pair of regions are known and fixed. These shipments are denoted by the matrix S, where each S_{ij}^d element equals the average annual commodity units shipped from Region i to Region j in Decade d. An optimal network design problem with fixed shipments, fixed link shipment costs, and a single period funding constraint on construction costs is referred by Magnanti and Wong (*5*) as a budget design problem with fixed costs and travel demands. The problem defined by Equations 1–5 extends this single-period problem to a multiperiod planning horizon.

$$\text{NIP1:} \qquad \min Z(G) = \sum_{d \in D} \sum_{i \in E} \sum_{j \in E} S_{ij}^d \, u_{ij}^d \, v^d \tag{1}$$

subject to:

$$\sum_{r \in R} \sum_{p \in P} c_{rp}^d \, x_{rp}^d \le F^d \qquad \text{for all } d \in D \tag{2}$$

$$\sum_{d \in D} \sum_{p \in P} x_{rp}^d \le 1 \qquad \text{for all } r \in R \tag{3}$$

$$x^d_{rp} = (0,1) \qquad \text{for all } r \in R,\ p \in P,\ d \in D \tag{4}$$

$$G = \{x^d_{rp} = 1 \qquad \text{for all } r \in R,\ p \in P,\ d \in D\} \tag{5}$$

where

- R = set of candidate improvement routes;
- P = set of candidate route improvement strategies, indexed from 1 to the maximum number of strategies defined for any given route;
- D = set of decades (10-year periods) in the planning horizon;
- E = set of 181 BEA regions as of 1989;
- G = set of route improvements programmed for each decade of the planning horizon;
- $Z(G)$ = total present value shipment cost of all interregional commodity shipments over minimum paths in G, which NIP1 seeks to minimize;
- S^d_{ij} = average annual commodity units shipped from Region i to Region j in Decade d (fixed in NIP1);
- u^d_{ij} = minimum path unit shipment cost from Region i to Region j over the improved Network G in Decade d (variable);
- v^d = present value discount factor that converts and sums annual shipment costs for Decade d into a single present value at Time 0 (fixed);
- x^d_{rp} = 1 if Strategy p is programmed for Route r in Decade d; 0 otherwise (variable);
- c^d_{rp} = construction cost of Strategy p for Route r in Decade d, expressed in present value dollars at Time 0 (fixed); and
- F^d = total funding available for route improvements in Decade d, expressed in present value dollars at Time 0 (fixed).

In this notation, each subscript pair rp denotes a set of link improvements for a given Route r and Strategy p, where Strategy 1 for Route 1 can be different from Strategy 1 for Route 2. Constraint Equation 2 ensures that construction costs for all programmed improvements are feasible within the funding constraints of all decades, and Equation 3 ensures that no more than one mutually exclusive route improvement strategy is included in the solution for each route. Alternative route improvement strategies for the same route are also mutually excluded from being programmed for more than one decade. Equation 5 defines a network improvement program G as a particular set of route improvements in each decade, and the expression for u^d_{ij} defines the minimum interregional shipment costs for a given network improvement program G.

A NETWORK IMPROVEMENT PROBLEM INVOLVING VARIABLE SHIPMENTS (NIP2)

The program given by NIP1 is to find the network improvement program G^* that is feasible within funding constraints and that minimizes the total present value cost of interregional commodity shipments carried over minimum cost paths. NIP2 is formulated in the same manner as NIP1 except that S^d_{ij} is variable instead of fixed. Cost-dependent shipments can be modeled within NIP2 by one of several alternative trip distribution forms, each being the solution to a nonlinear programming problem in which the objective is to maximize the statistical likelihood of the distribution matrix (given by the entropy function) subject to shipment production and attraction constraints at regions, and an average shipment cost constraint between regions (*9,10*). Equation 6 indicates the form of the origin-constrained shipment distribution used in the example presented later.

$$S^d_{ij} = A^d_i\, O^d_i\, D^d_j\, (u^d_{ij})^{-\beta} \qquad \text{for all } i \in E,\ j \in E \tag{6}$$

where

$$A^d_i = \left[\sum_{j \in E} D^d_j\, (u^d_{ij})^{-\beta}\right]^{-1} \qquad \text{for all } i \in E,\ d \in D;$$

- S^d_{ij} = average annual commodity units shipped from Region i to Region j in Decade d (variable in NIP2);
- O^d_i = average annual units shipped from Region i in Decade d (fixed); and
- D^d_j = total population of BEA Region j in 1985 (fixed).

Each balancing factor A^d_i causes Row i of S^d to sum properly, and results from the Lagrange multiplier on shipment productions from Region i in the maximum entropy trip distribution problem. The deterrence parameter β relates interregional shipment costs to shipment frequencies, and equals the Lagrange multiplier on average shipment cost in this problem. Shipments are assigned to minimum cost paths, but not all shipments from any origin are routed to their least cost destination. The power function form of the cost deterrence function is used here, rather than a negative exponential function. The power function results from replacing u^d_{ij} by ln u^d_{ij} in Wilson's maximum entropy formulation of this problem. In Equation 6, u^d_{ij} is raised to a negative power instead of being in the negative exponent itself. Interregional commodity shipment distributions using this power function form of the deterrence function have been shown to adequately fit survey data (*11*).

In the later example, each row total of S^d (denoted as O^d_i) equals total dollars of manufactured shipments and agricultural production from each BEA region as reported by the 1988 County and City Data Book (*12*). Because estimates of total shipments to each BEA region were not available from any known data source, the distribution of shipments to each BEA region was weighted on the basis of 1985 populations. The U.S. Bureau of Census is administering a 1989 survey of national commodity movements called the National Transportation Activity and Commodity Survey (NTACS) that will provide improved estimates both of origin and of destination shipment totals by county for 15 major industrial classes with which alternative forms of the shipment distribution model can be calibrated that are industry-specific. Although a commodity flow model for national network design should account for more industry specific factors affecting shipments between regions, the use of Equation 6 is sufficient to approximate changes in commodity shipments with network design.

For a given value of β in Equation 6, the total shipment cost will vary between alternative networks, which is the objective of network design problems NIP1 and NIP2 to minimize. The solution to NIP2 is a network that is optimal in the following sense: given that shipments S are calculated on the basis of Equation 6 for each network improvement program G, where each u^d_{ij} is the minimum path cost for each (i,j) pair and β is fixed, no other network improvement program results in a distribution with a lower transportation cost than the optimal network G^*. Boyce and Soberanes (*13*) formulate a problem similar to NIP2 in which the objective is to find the network with maximum distribution entropy subject to a mean shipment cost. Although this formulation has an appealing interpretation, it requires the calibration of β for each alternative network. Moreover, requiring average shipment cost to be constant in a network design problem for which the objective is to minimize this value presents a conflict. Hence, β was held constant in the example. If origin-destination data are available for multiple commodity types, then the distribution model can be generalized by commodity type with values of β specific to the cost-deterrence relationships of different commodity shipment patterns.

RANK-ADD-AND-SWAP HEURISTIC SOLUTION PROCEDURE (RASH)

Ranking and selection procedures are often used to determine project priorities on the basis of many considerations including project severities, geographical funding distributions, and benefit-cost analyses. For network design problems in which candidate improvements to a network have independent benefits, a once-through ranking and selection process might perform well as a heuristic solution technique. In network design problems of the type formulated earlier, an improvement to one route may affect the benefits of improving other routes, and some routes may overlap. Hence, this ranking and selection process must be performed sequentially and iteratively, recalculating the rankings of all remaining candidate route improvements after one or more changes to the network have been made in each iteration.

Several researchers (*14–17*) have described and tested branch-and-bound algorithms for solving discrete network design problems. Many of these algorithms are reviewed in the survey article by Magnanti and Wong (*5*). The number of networks to be examined by these branch-and-bound algorithms is quite large, because the bounding rules are generally weak and do not greatly reduce the computational burden of the search in problems that do not have clearly dominant choices. Only in cases where certain link additions are essential to creating shorter minimum paths is it found that the bounding rules achieve a significant reduction in search effort. On the other hand, heuristic solution approaches can considerably reduce the number of network evaluations required to obtain a good or near-optimal solution, particularly in problems with many closely competitive and near-optimal solutions.

Problems such as NIP1 and NIP2 are classic knapsack problems for cases in which the objective function and cost constraints are strictly linear, such that the impacts of all route improvements are independent of each other. A heuristic method of solving a knapsack problem with one cost constraint is to first rank the candidate items according to their benefit-cost ratios, and then to accept items into the solution from the best on down until no more items can fit within the single cost constraint. Integer programming algorithms designed to solve knapsack problems often use this approach to generate a good initial feasible solution from which to search for further improvements. Quite often, this initial solution is either an optimal solution or a close competitor. Moreover, any improvements to this initial solution often achieve only a small percentage improvement in the value of the objective function.

A benefit-cost or return-expense ratio is often used as an effective gradient measure in algorithms for solving zero-one programming problems (*18*). This ratio is simply a means of ranking alternative project candidates in each iteration after adjusting their costs and benefits to present values. Janson and Husaini (*19*) and Janson (*20*) successfully demonstrate the use of this ranking criterion in several heuristic algorithms for network design, and for regional highway programming problems in which projects have alternative start times subject to yearly budget and regional funding constraints.

In the rank-add-and-swap heuristic (RASH) solution procedure described next, route improvement strategies are ranked and added to the solution according to their ratios of benefit present value (BPV) to cost present value (CPV). BPV is the discounted reduction in the total shipment cost caused by a route improvement, and CPV is the discounted construction cost of a route improvement. Thus, any decrease in the value of the objective function corresponds to positive benefits, and any increase in the value of the objective function corresponds to negative benefits. An equivalent ranking criterion is NPV/CPV, where NPV is the net present value equal to BPV − CPV. Because NPV/CPV = (BPV/CPV) − 1, both ratios always yield identical rankings.

For adding a given improvement with indices (r,p,d) to the current solution G^n at Iteration n of the solution procedure, this benefit-cost ranking ratio is defined by

$$\mathrm{BCR}_{rp}^{dn} = [Z(G^n) - Z(G^{n+})]/c_{rp}^{d} \qquad (7)$$

where

$Z(G^n)$ = objective function value of current solution G, expressed in present value dollars at Time 0.
$Z(G^{n+})$ = objective function value of current solution G plus route improvement (r,p,d), expressed in present value dollars at Time 0.
c_{rp}^{d} = construction cost of Strategy p for Route r in Decade d, expressed in present value dollars at Time 0.

In each iteration of RASH, recalculating the benefit-cost ratio for each route improvement candidate requires updating all interregional minimum path shipment costs for each improvement considered in NIP1, and redistributing the commodity shipments among regions because of shipment cost changes in NIP2, in each decade. Then, changes to the objective function in each decade are discounted to Time 0.

If RASH were to add only one new route improvement to the current solution in each iteration, it would be excessively tedious for large problems or problems in which the evaluation of each route improvement requires a significant amount of computational effort, such as for shortest path and shipment distribution routines. Hence, RASH is designed to take a larger step towards the final solution in each iteration by adding several new route improvements to the current solution in each execution of Step 5. However, the larger step size may allow route improvements with interdependent costs and benefits to be added in the same iteration. Because interdependent candidates may not be as important to the solution in combination with others, a method is needed to delete some route improvement strategies from the current solution so that others can be added.

RASH allows the current solution to expand by several route improvements in each iteration, and also allows previously included improvements with inferior benefit-cost ratios to be deleted or switched with new improvements with superior ratios at that point in the solution process. Alternative improvements for routes that already have improvements in the current solution can also be substituted or switched for each other. Each iteration results in a new solution comprised of top-ranked budget-feasible improvements with respect to the previous solution subject to both "net" and "gross" step size limitations on the increment of total funding allowed to be programmed in each iteration.

In order to determine the composition of the new solution in each iteration, the RASH procedure computes changes in the objective function for each possible improvement addition or deletion as follows:

1. If an improvement strategy for Route r is not in the current solution G^n, then compute the decrease in the value of $Z(G^n)$ for each alternative improvement to Route r when added to G^n.
2. If an improvement strategy for Route r is in the current solution G^n, then compute the decrease in the value of $Z(G^{n-})$ for each alternative improvement to Route r when added to G^{n-}, where G^{n-} is equal to G^n without the current improvement to Route r.

Note that G^{n-} is defined as the current solution minus a particular route improvement strategy, whereas G^{n+} is defined for Equation 7 as the current solution plus a particular route improvement strategy. The difference is made solely to describe the conditions correctly. The second condition is worded to cover the evaluation of each already included route improvement strategy when removed from the current solution, because RASH allows deletions of improvements from the current solution so that other improvements can be added.

As stated earlier, increases and decreases in the value of the objective function correspond to negative and positive benefits, respectively. Because improvement deletions (or disimprovements) have negative construction costs, the benefit-cost ratio given by Equation 7 will always be positive for both improvements and disimprovements so long as route improvements never increase the total shipment cost and disimprovements never decrease the total shipment cost. This property must be true of any improvement or disimprovement to a network for problems NIP1 and NIP2 to be convex. This property may not be true of a network design problem with user equilibrium assignment, or in problem NIP2 if β is allowed to vary during the solution process.

The RASH procedure limits the number of route improvements added per iteration to the current solution with a net step size equal to some fraction of the total undiscounted construction funds initially allocated for the entire planning horizon. For example, if \$10 billion were allocated for each of three decades, a net step size of \$3 billion would allow the route improvements added in each iteration to have a total undiscounted cost of up to 1/10 of the initially allocated funds. This net step size would enable a final solution to be found in about 10 iterations. A gross step size, which might typically be set to twice the net step size, is also used to limit the amount that the current solution can depart from the previous solution because of improvement switching. However, the gross step size will only affect the solution process in cases where alternative route improvements have highly interdependent impacts on the costs and benefits of each other. The gross step size limit was never found to affect the solution process or the final solution in the example of this paper.

As a preview to the RASH procedure, candidate route improvements are ranked in descending order of their benefit-cost ratios, and the highest ranked feasible improvements are added to the current solution subject to the net and gross step size limitations and the available funds in each decade. The term "budget-feasible" means that a given route improvement strategy (r,p,d) can fit within the remaining funds available for Decade d when it is considered for addition to the current solution. The term "step-size-feasible" means that a given route improvement strategy (r,p,d) can fit within both the remaining net and gross step sizes of undiscounted funds when considered for addition to the current solution.

STEPS OF THE RASH SOLUTION PROCEDURE

1. Let G^n be the current subset of programmed route improvement strategies at Iteration n of this solution procedure. Discard any route improvement strategy (r,p,d) that is not budget-feasible within the funds allocated for Decade d (using unspent funds from previous decades if allowed). Begin with no route improvements such that G^0 is the existing network, and $x_{rp}^{dn} = 0$ for all (r,p,d) combinations. Specify the allowable net and gross step sizes per iteration (denoted as k and K, respectively) as portions of the total undiscounted initially allocated funds in all decades such that the final solution will be obtained within a reasonable number of iterations. Initialize n to 0, and go to Step 2.
2. Increment the iteration counter n to $n + 1$. Set the cumulative step size limit nk for Iteration n equal to the net step size k times the iteration counter. Reset the gross step size K to its original value defined in Step 1. Go to Step 3.
3. For each not-yet-improved route, compute the benefit-cost ratio BCR_{rp}^{dn} of each alternative route improvement strategy (r,p,d) if individually added to the current solution G^n as the change in the value of $Z(G^n)$ divided by the candidate's present value cost. For each already-improved Route r, evaluate the ratio of each alternative improvement to Route r as the change in the value of $Z(G^{n-})$ divided by the candidate's present value cost, where G^{n-} is equal to G^n minus the current improvement to Route r. All possible route improvements are considered to be budget-feasible in this step. Go to Step 4.
4. Rank all route improvement candidates evaluated in Step 3 in descending order of their benefit-cost ratios. An improvement strategy for a given route in a later decade is only ranked higher than an improvement strategy for the same route in an earlier decade if the later strategy has both a higher ranking ratio and a greater NPV. Go to Step 5.
5. If the rank-ordered list of route improvement candidates is empty, then STOP. Else, go to Step 6.

6. If the top-ranked route improvement candidates is budget feasible (using unspent funds from previous decades if allowed) and no other improvement has been included for this same Route r in this current iteration, then go to Step 7. Else, remove this candidate from the rank-ordered list, and return to Step 5.

7. If the top-ranked route improvement candidate is feasible within both the amounts of cumulative and gross step sizes remaining (nk and K), then go to Step 8. Else, return to Step 2.

8. Include the top-ranked route improvement candidate in the current solution G^n by setting its value of x_{rp}^{dn} to 1, and remove this candidate from the rank-ordered list. Subtract the undiscounted cost of this route improvement strategy from the cumulative step size nk, and also from the gross step size K if this candidate was not in the solution of the previous iteration. Update the remaining funds in Decade d, and return to Step 5.

Table 1 indicates how alternative route improvement strategies are ranked and added to solutions of the RASH procedure for the first two iterations, where the decade of construction is disregarded for example purposes. With a net step size of $400 million, eight route improvements could be included in the first iteration. These same route improvements are included in the second iteration, although with slightly different ranks because of interdependent costs and benefits. The second iteration includes 15 route improvements within the cumulative step size of $800 million for two iterations. Note that two route improvement strategies were passed over because improvements for these routes had already been included in the solution of this iteration.

The RASH procedure does not require an individual route improvement strategy to have an economically acceptable benefit-cost (B/C) ratio as a condition of acceptance for two reasons. First, with interdependent effects, individual route improvements with B/C ratios below one when evaluated individually may have B/C ratios above one when evaluated with other route improvements. Second, a full accounting of all costs and benefits may not be possible within the context of the analysis, and the purpose of the analysis is to determine a best design for the costs and benefits that are recognized, allowing that benefits may be underestimated. Problems NIP1 and NIP2 as formulated do not include any benefits to personal travel, impacts on business development, or any other economic or environmental effects.

EXAMPLE APPLICATIONS OF RASH TO AN NIP2 PROBLEM

An example is presented of applying the strategic network improvement planning approach described earlier to potential improvements of 289 major highway routes between adjacent BEA regions that cover the 48 contiguous states of the United States. These routes connect the geographic population centroids (as of 1985) of 181 BEA regions (as defined in 1989), and are mostly composed of Interstates, four-lane urban highways, and rural principal arterials.

The National Highway Planning Network connecting these regions was developed at Oak Ridge National Laboratory to support a wide variety of national transportation analyses, primarily for the U.S. Departments of Energy, Defense, and Transportation. The full network (as of 1989) contains approximately 370,000 mi of roads to varying degrees of accuracy in both its geographic and attribute data, and is currently used by the Office of Transportation Systems, FHWA, for analytical modeling and forecasting purposes. In addition to the $X-Y$ coordinate pairs needed to describe each link's geographical location and alignment, the network data base has 17 other attributes defined for each link as follows:

1. Link ID,
2. Sign route,

TABLE 1 EXAMPLE OF ROUTE IMPROVEMENT RANKINGS AND SELECTION

				Iteration #1						Iteration #2	
r	p	Cost	Cost Sum*	Ratio	In/Out	r	p	Cost	Cost Sum*	Ratio	In/Out
15	2	32	32	2.571	In	14	1	92	92	2.493	In
14	1	92	124	2.494	In	15	2	32	124	2.424	In
2	1	71	195	2.364	In	6	1	11	135	2.326	In
16	2	91	286	2.321	In	2	1	71	206	2.220	In
6	1	11	297	2.290	In	3	1	32	238	2.189	In
3	1	32	329	2.252	In	16	2	91	329	2.172	In
19	2	27	356	2.202	In	19	2	27	356	2.079	In
17	1	27	383	2.183	In	17	1	27	383	2.042	In
5	1	39	---	2.027	Out	5	1	39	422	1.842	In
8	1	19	---	1.834	Out	4	2	57	479	1.661	In
11	1	76	---	1.776	Out	8	1	19	498	1.623	In
4	2	57	---	1.750	Out	11	1	76	574	1.579	In
6	2	92	---	1.587	Out	6	2	92	---	1.512	Out
2	2	84	---	1.579	Out	2	2	84	---	1.413	Out
12	2	53	---	1.377	Out	12	2	53	627	1.278	In
18	1	72	---	1.365	Out	18	1	72	699	1.170	In
13	1	47	---	1.231	Out	13	1	47	746	1.162	In
8	2	84	---	1.132	Out	8	2	84	---	1.061	Out
4	1	29	---	1.044	Out	15	1	62	---	0.907	Out
1	1	40	---	0.969	Out	4	1	29	---	0.896	Out
15	1	62	---	0.917	Out	1	1	40	---	0.855	Out

* All costs are in millions of dollars. The cost sum is the running total cost for included route improvement strategies.

3. Length,
4. Heading,
5. Urban flag,
6. One-way flag,
7. Median division,
8. Access control,
9. Number of lanes,
10. Traffic restriction identifier,
11. Toll flag,
12. STAA truck route flag,
13. Principal highway extension,
14. Pavement type,
15. Administrative class,
16. Functional class, and
17. Existing or proposed link.

The geographical coordinates of links and nodes in the highway network data base were obtained primarily from a set of road maps digitized by the U.S. Geological Survey (USGS) from 1:2,000,000 scale plates of the National Atlas. Additional maps ranging in scale from 1:100,000 to 1:250,000 obtained from state highway agencies and other departments were also used to supplement the development of this network. Approximate percentages of road mileage by functional class in the full network of 370,000 mi are as follows:

Percentage	*Road Category*
5.7	Interstates (rural, urban, and rural/urban)
21.9	Rural or rural-urban principal arterials
31.8	Urban principal arterials and other arterials
9.0	Collectors and other minor arterials
31.6	Unknown or unclassified in the network

The entire U.S. highway network data base contains roughly 42,000 links and 27,000 nodes. For this network improvement analysis, a subnetwork of major intercity highways was extracted from the full network, including all links in the first two functional class groupings listed, plus some from the third group. Links in the extracted network were combined into longer links over which attributes important to this analysis did not vary. These attributes were

- Number of lanes,
- Whether or not opposing lanes of traffic are divided by a median strip or barrier, and
- Whether or not access to the lanes is controlled by entrance and exit ramps.

This network extraction and condensing process resulted in a subnetwork of 137,338 mi (or 37.1 percent of the full network mileage) with 7,775 links and 5,620 nodes. This subnetwork, shown in Figure 1, referred to as the "analysis network," was used in all test runs of the RASH procedure, including those for the following example.

Figure 2 shows the boundaries of the 181 BEA regions as they were defined in 1989. Figure 3 shows an enlarged portion of Figure 2 for three BEA regions in southern Texas with the analysis network of Interstates, four-lane urban highways, and rural principal arterials crossing these regions. Highlighted in bolder lines is the initial minimum-cost path between the 1985 population centroids of the Corpus Christi and Brownsville-McAllen-Harlingen BEA regions.

In Figure 3, the width of the initial minimum-cost path from Corpus Christi to Brownsville corresponds to the number of existing lanes along each segment of this route. Table 2 presents the link characteristics of this route for its existing status and with each improvement strategy. The two improvement strategies considered for each route are to make all necessary

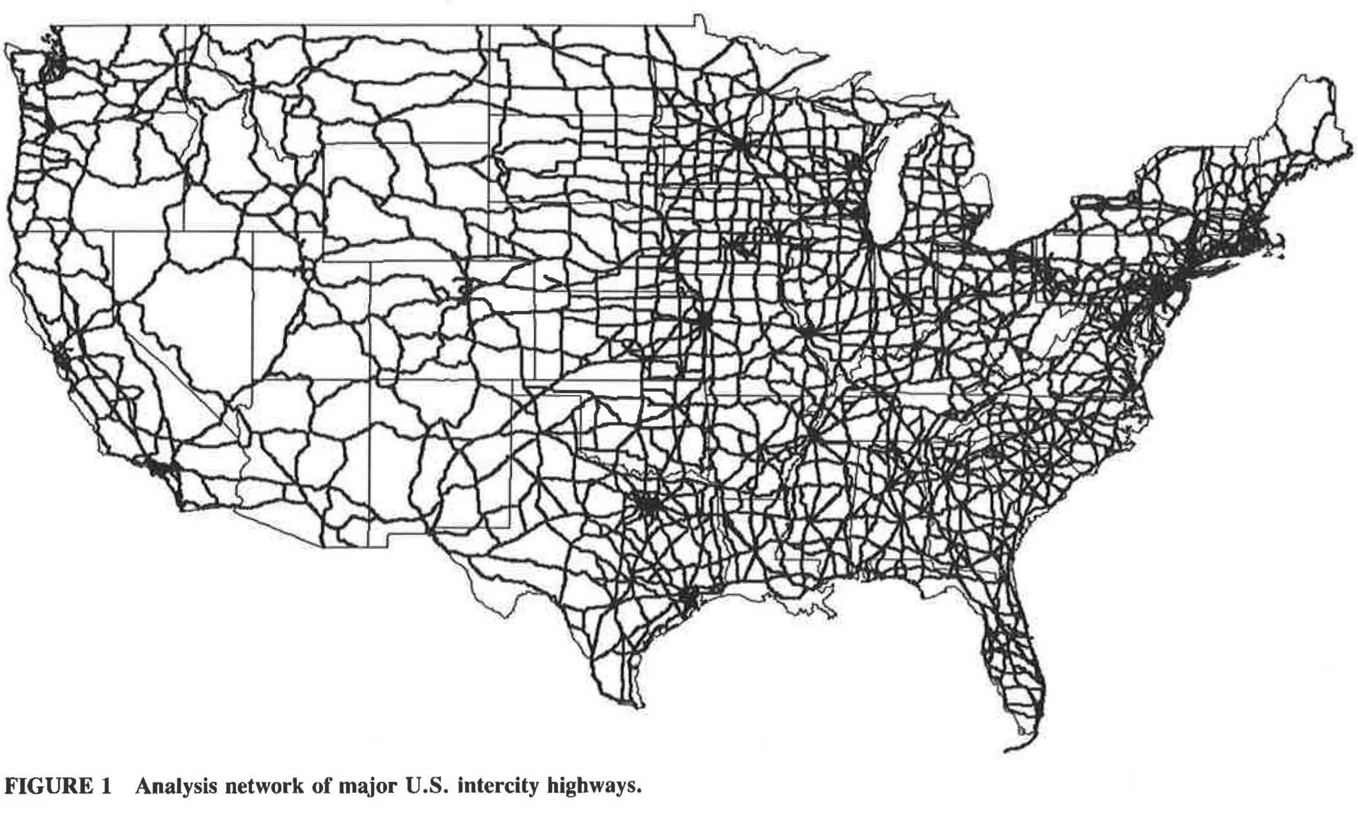

FIGURE 1 Analysis network of major U.S. intercity highways.

FIGURE 2 The 181 BEA regions in the 48 contiguous states of the United States.

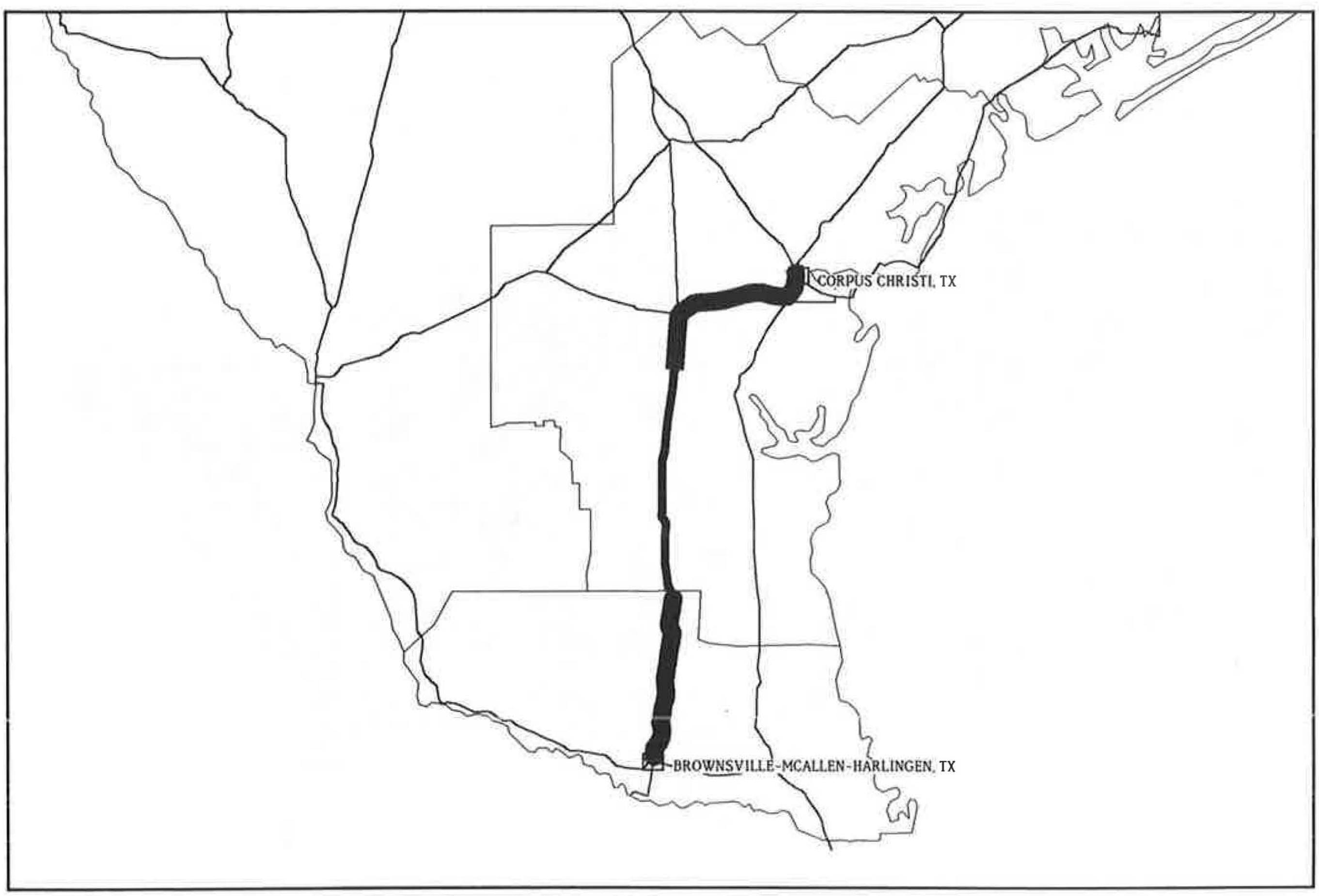

FIGURE 3 A candidate improvement route in the analysis network—minimum-cost path from Corpus Christi to Brownsville, Texas.

TABLE 2 LINK ATTRIBUTES OF THE CANDIDATE IMPROVEMENT ROUTE

Existing Attributes

Link ID	# of Lanes	Divided Median	Access Control	Speed (mph)	Length (miles)	Travel Time (min)
1	4	No	No	37.5	5.8	9.3
2	4	Yes	No	37.5	27.1	43.4
3	4	Yes	No	37.5	13.4	21.4
4	2	No	No	26.9	54.9	122.3
5	4	Yes	No	37.5	15.0	24.0
6	4	Yes	No	37.5	25.2	40.3
				32.5	141.4	260.7

Improvement Strategy 1 (undiscounted cost = $\$1134.5 \times 10^6$)

Link ID	# of Lanes	Divided Median	Access Control	Speed (mph)	Length (miles)	Travel Time (min)
1	4	Yes	Yes	65.0	5.8	5.4
2	4	Yes	Yes	65.0	27.1	25.0
3	4	Yes	Yes	65.0	13.4	12.4
4	4	Yes	Yes	65.0	54.9	50.7
5	4	Yes	Yes	65.0	15.0	13.8
6	4	Yes	Yes	65.0	25.2	23.3
				65.0	141.4	130.6

Improvement Strategy 2 (undiscounted cost = $\$219.6 \times 10^6$)

Link ID	# of Lanes	Divided Median	Access Control	Speed (mph)	Length (miles)	Travel Time (min)
1	4	No	No	37.5	5.8	9.3
2	4	Yes	No	37.5	27.1	43.4
3	4	Yes	No	37.5	13.4	21.4
4	4	No	No	37.5	54.9	87.8
5	4	Yes	No	37.5	15.0	24.0
6	4	Yes	No	37.5	25.2	40.3
				37.5	141.4	226.2

Note: Average (not total) route speed shown below speed column.

upgrades so that (a) every link is median divided with controlled access and at least four lanes, or that (b) every link is at least four lanes, but without any changes to median division or access control.

Table 3 presents link attributes and mileages of all 289 routes considered for improvement. These routes comprise 64,444.8 mi of the 137,338 mi (or 47 percent), and 3,309 links of the 7,775 links (or 43 percent), of the entire analysis network. Because Strategy 2 is only applicable to routes with two-lane links, there are 536 possible route improvements (289 of Strategy 1, and 247 of Strategy 2). Table 3 presents the road mileages of all 289 routes by their link attributes for three extreme cases: (a) no improvements, (b) all 247 Strategy 2 improvements, or (c) all 289 Strategy 1 improvements.

Unit shipment costs were assumed to be directly proportional to route travel times. Link travel times were computed

TABLE 3 SUMMARY OF ALL POSSIBLE ROUTE IMPROVEMENTS BY STRATEGY TYPE

# of Lanes	Divided Median	Access Control	Speed (mph)	Road Mileages by Link Type: Existing Routes	All 2nd Strategy	All 1st Strategy
2	No	No	26.9	20556.9	0.0	0.0
2	No	Yes	45.5	223.1	0.0	0.0
4	No	No	37.5	432.7	20989.6	0.0
4	No	Yes	65.0	2.1	225.2	0.0
4	Yes	No	37.5	7364.2	7364.2	0.0
4	Yes	Yes	65.0	35534.4	35534.4	64113.4
>4	Yes	Yes	65.0	331.4	331.4	331.4
			totals =	64444.8	64444.8	64444.8

Total undiscounted cost of all strategy 1 improvements = $\$275,789 \times 10^6$
Total undiscounted cost of all strategy 2 improvements = $\$83,566 \times 10^6$

as over-the-road distances divided by average travel speeds as reported by FHWA for functional road classes. Link travel times were then increased by 20 percent for roads with uncontrolled or partially controlled access because of intersection delays, and by another 10 percent for two-lane roads because of slow vehicle impedances. In order to compute shipment costs, the link travel times were multiplied by a fixed value per minute of travel time saved per million dollars of goods being shipped. For the type of shipment distribution function used in this example, the value of time will not affect the selection of route improvement strategies because its value will not alter the shipment distribution or relative sizes of benefit-cost ratios used to rank alternative route improvements during the solution process.

This example is for a 30-year planning horizon beginning in 1990 in which total commodity shipments to and from each region are forecasted for each year of each decade. Route improvements can be programmed for construction in any decade, but the total construction cost of all route improvements programmed must be within the 10-year funding allocation of each decade. Route improvement construction costs were computed on a lane-mile basis according to recently reported costs for road widening. Construction costs were assumed to be the same in each decade for each project in terms of undiscounted 1990 dollars, and the same level of funding in undiscounted 1990 dollars was used as the budget constraint in each decade.

Forecasts of shipment origins from each region in each year of the planning horizon were made on the basis of economic activity data for the counties of each region obtained from the 1988 County and City Data Book (*12*). The total value of shipments from each region was assumed to be proportional to the dollar value of manufactured goods shipped from each region plus the dollar value of farm production in each region, which is less than 7 percent of these two values combined for the nation as a whole. These two product groups account for roughly 80 percent of all U.S. truck vehicle-miles of travel when such ambiguous goods as building products are defined as manufactured goods.

The 1988 estimated shipments from each region were assumed to grow at a rate of 3 percent per year over the entire planning horizon. Thus, shipment estimates for 1991 were already greater than the 1988 estimates by more than 9 percent with compounding. The 1985 population of each region was then used to weight the total value of shipment destinations to each region. The population of each BEA region was assumed to increase at a uniform rate for all regions in every year of the planning horizon.

The value of time for commodity shipments was assumed to be the same per dollar of good shipped regardless of product type. Other carrier costs for labor and equipment were not included in the analysis, because these varied with fleet and vehicle size. The commodity shipment data in this example are only intended to represent surrogate measures of shipment generation and attraction rates that are realistically proportional to the actual magnitudes of shipments between regions.

A discount rate of 10 percent per annum was applied both to the costs and to the benefits of all network improvement strategies. All improvement strategy costs and funding allocations were averaged over each decade as uniform series. Uniform series discount factors were applied to these cost and funding streams in order to express all amounts in 1990 present value dollars. The total shipment cost reduction in each year brought about by a given improvement was discounted to 1990 dollars, and the reductions for each year were summed to equal the total present value of improvement benefits.

In this example, a budget constraint of $27,579 million (undiscounted) was allocated for route improvements in each decade, which equals 10 percent of the total undiscounted cost of all 289 Strategy 1 improvements to all routes. Table 4 presents the road mileage changes over time in the RASH solution to this example by the attributes listed because of the route improvements made in each decade. Table 5 indicates that a total of 9,050 mi of highway are to be improved by Strategy 1, and 839 mi of highway are to be improved by Strategy 2.

Table 6 presents the benefit-cost ratio for each decade of route improvements in the RASH solution to this example and for the entire planning horizon. The freight shipment costs exhibited are estimated on the basis of total travel time required. The freight shipment costs represent estimated travel time costs assuming an average commodity shipment value of $10,000 per truck and an average truck value-of-time of $15 per hour. The values labeled as being without improvements indicate how much worse the freight shipment costs would have been had these route improvements not been made and no other improvements substituted for them. Table 6 indicates an average truck trip travel time decrease of 14.5 min because of all route improvements. This average travel time savings is for all truck trips, not just those using improved routes.

The discounted benefit-cost ratio increases in each successive decade because of the 3 percent annual growth rate in total shipment value. In computing this ratio, both route improvement costs and shipment cost savings are discounted by the same annual discount factor, where the route improve-

TABLE 4 ROAD MILEAGE IMPROVEMENTS IN THE RASH SOLUTION

			Road Mileages by Link Type			
# of Lanes	Divided Median	Access Control	Existing Routes	End of Decade 1	End of Decade 2	End of Decade 3
2	No	No	20556.9	18847.5	16866.1	14980.7
2	No	Yes	223.1	119.4	107.5	72.3
4	No	No	432.7	716.4	1057.5	990.0
4	No	Yes	2.1	97.4	97.4	97.4
4	Yes	No	7364.2	5723.8	4383.7	3388.3
4	Yes	Yes	35534.4	38608.9	41601.2	44584.7
>4	Yes	Yes	331.4	331.4	331.4	331.4
		totals =	64444.8	64444.8	64444.8	64444.8

TABLE 5 SUMMARY OF ROUTE IMPROVEMENTS IN THE RASH SOLUTION

	Strategy 1	Strategy 2	Total
Decade 1			
1) miles improved	3075	477	3551
2) number of routes	56	14	70
3) undiscounted cost	25571	2001	27572
Decade 2			
1) miles improved	2992	363	3355
2) number of routes	43	6	49
3) undiscounted cost	26126	1451	27577
Decade 3			
1) miles improved	2984	0	2984
2) number of routes	28	0	28
3) undiscounted cost	27569	0	27569
All Decades			
1) miles improved	9050	839	9890
2) number of routes	127	20	147
3) undiscounted cost	79266	3452	82718

Note: All costs are in millions of undiscounted 1990 dollars.

TABLE 6 BENEFIT-COST COMPARISON OF THE RASH SOLUTION

	Decade 1	Decade 2	Decade 3	Total
Undiscounted Values				
Total shipment value	22790762	30628878	41162651	94582291
Total shipment cost				
1) without improvements	503973	677298	910231	2091502
2) with improvements	498070	666121	892868	2057059
3) reduction (= benefits)	5903	11177	17363	34443
Average shipment travel time with improvements (minutes) (884.5 without improvements)	874	870	868	870
Total strategy cost	27572	27577	27569	82718
Discounted Values				
Total shipment cost				
1) without improvements	302622	156800	81244	540666
2) with improvements	299078	154212	79694	532984
3) reduction (= benefits)	3544	2588	1550	7682
Total strategy cost	16942	6533	2518	25993
Total benefit/cost ratio	0.209	0.396	0.616	0.296

Note: All costs, benefits, and shipments are in millions of dollars.

ment costs are assumed to be spread uniformly over each decade. Although the end of the planning horizon truncates the benefit stream for each improvement, the relative rankings of projects in a common decade will be unaffected by the end of the planning horizon. Hence, using a finite or infinite planning horizon will have little impact on the RASH solution to this example.

CONCLUSIONS

A heuristic network design procedure for the selection and programming of major route improvements to the national highway network has been presented. The solution outcome of this procedure relies heavily on the suitable definition and assessment of the net benefits and costs of alternative system design plans. Beyond the simplified treatment of benefits and costs used in this paper, system benefits should also include accident reductions, access improvements, economic development impacts, environmental effects, and energy considerations. System costs must be made more specific as to the design and construction requirements of alternative strategies for different routes, because construction costs can be several times greater than the average for sites with different terrain or environmental complications.

These requirements are indeed burdensome for large problems that may, in fact, possess several good solutions, any one of which is not so difficult for a heuristic to reliably obtain. In cases where several good solutions satisfy the desired goals of a broader decision making process, the heuristic solution procedure can be used to investigate the sensitivity of competing solutions to different cost and benefit assumptions at moderate computational expense. Then, both human and computer resources can be focused on the generation and evaluation of alternative problem specifications, which are critical to completeness of the overall design process.

The results of this study show that a relatively straightforward and computationally less burdensome heuristic solution approach can be successfully applied to evaluate alternative highway network improvement programs for several future decades. The integration of this approach with geographic data bases, network link files, and highway information management systems facilitates the preparation and execution of alternative travel demand forecasts and funding scenarios. Although codes for the heuristic solution approaches described herein can be developed and implemented easily on microcomputer workstations, it would be difficult to solve these same problems with integer programming optimization packages.

The imposition of a budget constraint on highway expenditures in each decade can be relaxed to determine the funds needed to achieve desired benefit levels over the planning horizon. Equity constraints in the form of regional funding requirements or net present value constraints can also be added to the model that require each region to receive a given amount of funds in each decade (*20*). In the presence of such equity constraints, route improvements are selected within regions so as to achieve maximum net present value for the entire system subject to these constraints.

Additional data are needed, particularly by commodity type, to improve the form and implementation of the shipment distribution model used in the example of this paper. The U.S. Bureau of Census is currently administering NTACS for 1989, which will provide better estimates of both origin and destination shipment totals of tons and dollar values by 15 major industrial classifications. The NTACS data may allow alternative forms of the distribution model to be calibrated and tested for use in this network improvement programming process. Other data sources must be garnered for better carrier and shipper cost data in relation to highway improvements.

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